Aquifer Testing Study
Work Plan

West County Road 112 Ground Water Plume Site
Midland County, Texas

EPA Region 6 Remedial Action Contract 2
Contract: EP-W-006-004
Task Order: 0065-RICO-A6R6

Prepared for

U.S. Environmental Protection Agency
Region 6
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1. INTRODUCTION

EA Engineering, Science, and Technology, Inc. (EA) prepared this Work Plan to perform single-well recovery aquifer testing at the West County Road 112 Ground Water Plume (WCR 112) site located in Midland County, Texas. This Work Plan was prepared for the U.S. Environmental Protection Agency (EPA) as part of Task Order No. 0065-RICO-A6R6.

2. SITE BACKGROUND

The WCR 112 site is located north and south of U.S. Interstate Highway 20 (I-20), within and south of the city limits of Midland in Midland County, Texas (Figures 1 and 2). The site consists of a chromium plume in the ground water which extends from an industrial area on the north side of I-20 across the highway to the south for approximately 1.4 miles in a mixed residential, commercial, industrial, and agricultural property area (Texas Commission on Environmental Quality [TCEQ] 2010a, 2010b). Based on contaminant distribution, the ground water flow in the area appears to be from northwest to south-southeast (Figures 3 and 4).

The ground water is the sole source of potable water in the area. The contaminant plume has impacted both private residential wells and supply wells that serve residences, commercial and industrial properties, and agriculture. Filtration systems have been installed by the TCEQ on private wells with concentrations above the EPA Maximum Contaminant Level (MCL) for total chromium of 100 micrograms per liter (µg/L). The contamination has been detected in both the shallow Ogallala Formation and the deeper Edwards-Trinity Formation Aquifers at depths of approximately 50–100 feet below ground surface (bgs).

3. OBJECTIVE

The objective of this study is to conduct aquifer testing to evaluate hydrogeologic conditions within the Ogallala Formation and Edwards-Trinity Aquifer to support ground water modeling. The aquifer testing will be conducted to establish sustainable flow rates, determine the permeability and hydraulic conductivity of the water-bearing zones tested, and to assess the well capacities for remedial design.

4. SCOPE OF WORK

Single-well pumping tests will be conducted at the WCR 112 site in the Ogallala and Edwards-Trinity Formation water-bearing zones (Figure 2). The tests will yield transmissivity and permeability (Kruseman and de Ridder 1991; Driscoll 1986). These data will result in a more accurate representation of the system for fate and transport models with respect to permeability and retardation of hexavalent chromium. Slug tests will be performed in several wells completed in the Edwards-Trinity Formation that have been shown to recover slowly during sampling activities. This information should further constrain the values of hydraulic conductivity to be incorporated into the model.

4.1 SINGLE-WELL RECOVERY TESTS

Single-well recovery tests (Kruseman and de Ridder 1991; Driscoll 1986) will be performed on the monitoring wells listed in Table 1. The Ogallala wells will be pumped at a constant rate for a period sufficiently long enough to overcome casing storage effects (Kruseman and de Ridder, 1991; Schafer, 1978). Pumping rate and stabilized drawdown (specific capacity) will be used to estimate transmissivity as follows:

$$T = 1500*Q/s$$

where: Q = discharge in gallons per minute (gpm)
s = drawdown in feet
T = transmissivity in gallons per foot per day.

Transmissivity will, in turn, be used to estimate critical pumping time:

$$t_c = (375*R^2)/T$$

where: R = casing radius in feet
t_c = critical pumping time.

Data will be analyzed by the Cooper-Jacob Method (Kruseman and de Ridder 1991; Driscoll 1986). Late-time recovery data will be analyzed because of the unconfined nature of the Ogallala Aquifer (Kruseman and de Ridder 1991).

Pumping will be accomplished with a Grundfos RediFlo2® capable of pumping less than 1 and up to 5 gallons per minute. During each test, water level drawdown while pumping and water level recovery after pumping will be monitored with data-logging pressure transducers (automated). The 2-inch-diameter well casings used in these tests preclude manual gauging as backup. Data-logging pressure transducers (LevelTROLL® 700) will be placed in each well prior to the start of each test. The transducer is capable of measuring water levels to within an accuracy of 0.01 foot. The transducer will be set below the pump and securely supported above the bottom of the well.

The pump will be equipped with a check valve to prevent backflow of water into the well after the pump is shut off. After the pump, discharge line, and flow meter are installed, the transducer will be calibrated against the water level as measured from the top of casing with the water level indicator, and the data logger will be set to record water level measurements at an interval appropriate for analysis. After the pump is placed within a well and before the pump is started, water levels will be monitored to evaluate equilibration. The pump will be turned on to start the test only after water levels have stabilized.

Each single-well test will begin by starting the pump and then monitoring flow and depth to water. Pumping rates will be measured and recorded at frequent time intervals and controlled using electronic controls that allow matching the frequency of the pump in hertz to observed pumping rates determined with an in-line flow meter/calibrated 5-gallon bucket and stopwatch. Optimal pumping rates will be selected based on the observed drawdown in each well; once a quasi-steady state drawdown is reached, the specific capacity will be used to establish appropriate pumping periods. Pumping durations and flow rates will be recorded.

During the drawdown phase of the single-well recovery tests, the field crew will review water level data relative to pumping rate (e.g., specific capacity) to estimate transmissivity, and in turn, critical time and pumping periods for the respective single-well tests. The critical time is the required pumping period to overcome casing storage effects and render the recovery data reliable. Wells will then be pumped at a constant rate for a period of several estimated critical times, thereby ensuring the tests are valid.

Data recorded during the tests will include clock time, elapsed time since pumping start, depth to water, the pumping rate, and total gallons of discharge. The pumping test field form is attached in Appendix A. The pump will be turned off at the end of the drawdown phase and recovery monitored until the water level is at about 95 percent of the static (pre-test) water level. Data will be downloaded from the transducer at the end of both the pumping and recovery periods using WinSitu® Software, version 5.6.9.7.

Single-well tests are designed to achieve constant discharge for a period long enough to overcome casing storage effects. Key data include: (1) time pump on, (2) flow rate (constant), (3) specific capacity (Q/s), (4) time pump off, and (5) gauged water levels throughout pumping and recovery periods.

Equipment required includes:

- Grundfos RediFlo2® Pump
- In-line flow meter
- 5-gallon bucket with gallons marked
- New, disposable polyethylene tubing appropriate for the RediFlo2® Pump
- Hermit LevelTROLL® Model 700 vented transducer
- Flat-bed trailer with polyethylene tanks for wastewater storage
- 500-barrel (21,000 gallon) fractionation (frac) tank
- Centrifugal pump for transfer of pumped water to frac tank
- Generator
- Two water level indicators (one to be used to set the pump)
- Two laptop computers with WinSitu® software (one computer as a backup).

4.2 STEP TEST

Utilizing TCEQ well TCEQ-MW-02, which is located within the center of mass of the chromium plume (Figure 5), a step test will be implemented to monitor the behavior of this well while pumped at three varying and increasing rates over time. Flow rate 1 will be such that drawdown is 1 to 2 feet, and the well will be pumped for a period of 30 minutes while monitoring drawdown. At the completion of the 30-minute period, the flow rate will be increased so that total drawdown is 5 to 7 feet (the rates may change based upon observed field conditions) and monitoring of drawdown will commence as in Step 1. Step 3 will proceed as the two steps before it so that drawdown is approximately 5 feet above the pump intake. At the conclusion of the step test, a single-well test will be implemented as described above.

Data will be analyzed by the Cooper-Jacob Method (Kruseman and de Ridder 1991; Driscoll 1986). Late-time recovery data will be analyzed because of the unconfined nature of the Ogallala Aquifer (Kruseman and de Ridder 1991). Equipment for the step test is the same as for the single-well tests.

4.3 SLUG TESTS

Slug tests will be performed on several wells that have been completed in the Edwards-Trinity Aquifer on the north side of I-20 (Figure 2). A geophysical survey determined the sediment surrounding these wells is finer-grained, and recent sampling events have shown they recover at very slow rates. The proposed slug test is a method developed by Bouwer and Rice (1976) for determining hydraulic conductivity from the sudden removal of a slug of water. The method is effective for evaluating wells completed in low permeability sediments, and should help better constrain the hydraulic conductivity of the water-bearing zones in the vicinity of these slow recovery wells.

Rising head slug (e.g., rapid removal of casing storage) tests will be conducted at slow recovery monitoring wells on the north side of I-20. The pump and transducer will be installed as described above for a single-well recovery test. The wells will be allowed to equilibrate after placement of the transducer and pump into the well, and then the well will be pumped out rapidly with the discharge valve fully open. Once the pump is shut off, rising water levels will be monitored manually with a water level meter and a data-logging transducer.

Following removal of the slug of water, recovery will be gauged in the well until 95 percent of the static condition is achieved. Initial displacement and recovery will be analyzed using AQTESOLV and the method of Bouwer and Rice (Bouwer and Rice 1976; Kruseman and de Ridder 1991).

Equipment required for these tests is the same as for the single-well recovery tests with the following exceptions: instead of a RediFlo2® Pump, a smaller, more manageable pump will be utilized (MegaMonsoon or similar). This will allow the pump to be deployed and removed from the well at a much faster rate than the RediFlo2®. In addition, a total of three transducers will be utilized for these tests, with the anticipation that wells tested in this manner may take 1 day or more to recover. Having extra transducers allows EA to perform multiple slug tests at once.

4.4 PUMPED WATER TREATMENT, STORAGE, AND DISPOSAL

Ground water pumped from each monitoring well will be discharged into a 500-gallon polyethylene tank secured on a flat-bed trailer. This wastewater will be transferred to a frac tank for profiling and disposal. A goal of the testing regimen is to produce an aggregate volume of wastewater that is below the MCL for chromium of 100 µg/L. An estimate of the chromium concentration of pumped water has been calculated for each well used in the test, based on previous concentration data (Table 2, Figures 5 and 6). During the pumping test, the pumping rate, pumping duration, and volume pumped from each well will be recorded, and the mixed concentration calculated to achieve this goal. The field form for tank concentration monitoring is included in Appendix A. At the completion of the tests, a sample will be collected from the tank and analyzed for Toxicity Characteristic Leaching Procedure (TCLP) volatile organic compounds, TCLP metals, reactivity, corrosivity, and ignitability. Once profiled, the wastewater will be disposed of in a similar manner as investigation-derived waste generated during the Remedial Investigation well drilling program.

4.5 DELIVERABLE

Following the aquifer test and receipt of analytical results, EA will analyze the data and prepare an Aquifer Test Technical Memorandum. The Memorandum will provide the following:

- Summary of field activities and methodology
- Pumping test design
- Copies of well logs for wells used in the test
- Raw data downloaded from transducers and presented in spreadsheet fashion
- Field forms, manually recorded data, field notes, and photographic documentation
- Data plots and curves for drawdown and recovery
- Corrections to data, if applicable
- Method of analysis and graphs of analysis
- Disposition of investigation-derived waste (e.g., wastewater)
- Interpretation of data.

5. REFERENCES

Bouwer, H. and R.C. Rice. 1976. A Slug Test Method for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells. *Water Resources Research*. 12(3): 423-428.

Driscoll, F.G. 1986. *Groundwater and Wells.* 2nd Edition. Johnson Filtration Systems. St. Paul, Minnesota.

Kruseman, G.P., and de Ridder, N.A. 1991. *Analysis and Evaluation of Pumping Test Data.* 2nd Edition. Publication 47. International Institute for Land Reclamation and Improvement. The Netherlands.

Schafer, D.C. 1978. Casing Storage Can Affect Pumping Test Data. *The Johnson Drillers Journal.* January-February.

Texas Commission on Environmental Quality (TCEQ). 2010a. *Site Inspection Report. West County Road 112 Groundwater*. *Midland, Midland County, Texas. TXN000606992.* February.

TCEQ. 2010b. *Expanded Site Inspection Report. West County Road 112 Groundwater. Midland, Midland County, Texas. TXN000606992.* July.

Tables

TABLE 1. PUMPING TEST WELL CONSTRUCTION SUMMARY FOR AQUIFER TESTING STUDY

Well	Screen Interval (feet btoc)	Schedule 40 PVC Casing Diameter (inches)	Depth to Water - June 2012 (feet btoc)	Height of Water Column (feet)
Ogallala Wells				
WMW-02A	35-55	2	21.53	36
WMW-03A	30-50	2	33.47	19
WMW-05A	40-45	2	36.95	10
WMW-06A	28-43	2	34.82	10
WMW-15A	27-47	2	36.92	12
WMW-17A	30-50	4	18.52	33
WMW-24A	28-48	2	19.77	30
WMW-27A	25-45	2	19.50	28
WMW-34A	28-48	2	21.28	29
WMW-37A	30-50	4	18.24	34
TCEQ-MW-02	16-56	4	23.72	32
Edwards-Trinity Wells				
WMW-05B	67-72	2	37.57	36
WMW-11B	52-72	2	42.00	32
WMW-21B	81-91	2	18.51	74
WMW-32B	73-83	2	22.55	62

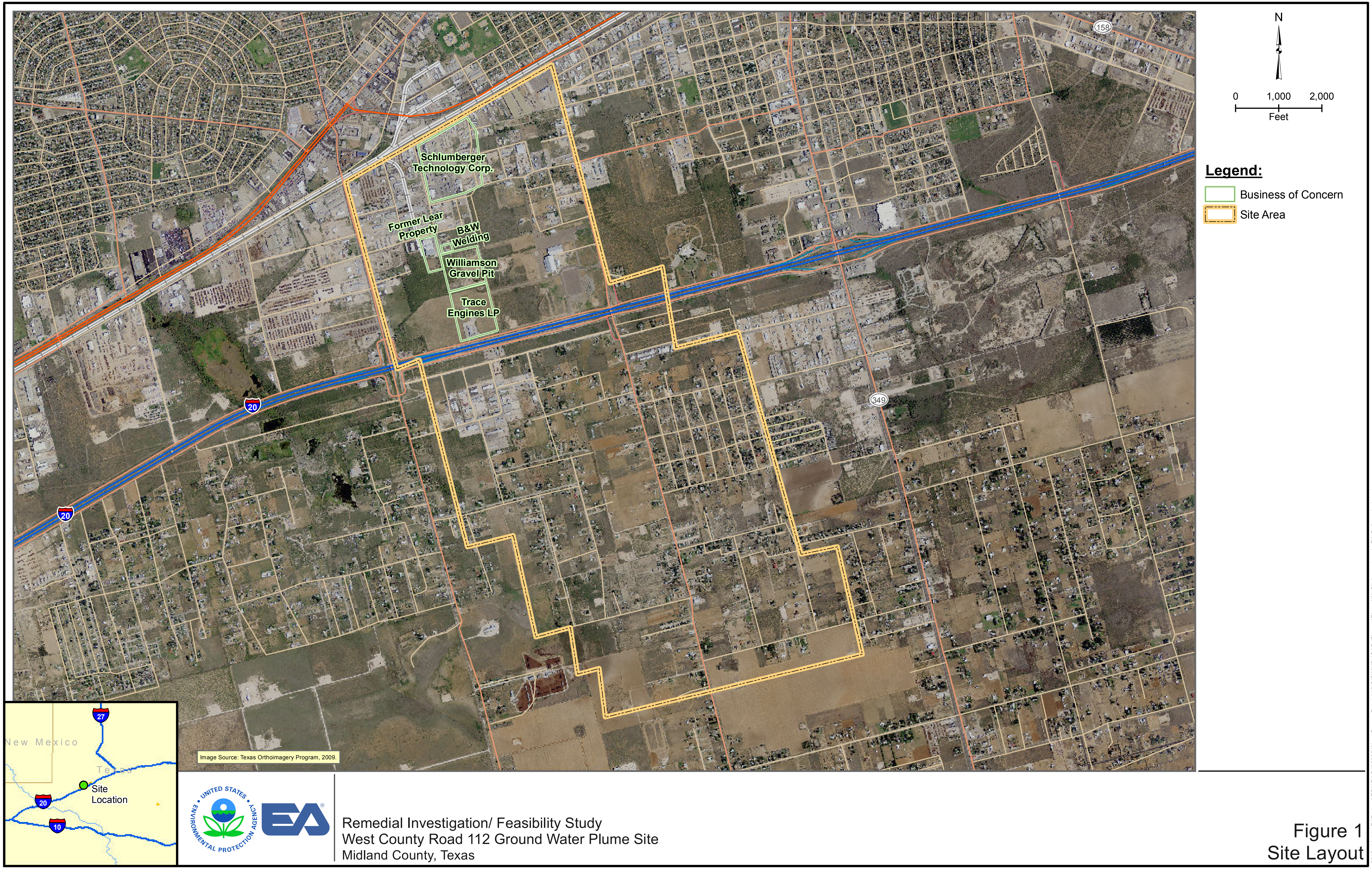
NOTE:
btoc = below top of casing
PVC = polyvinyl chloride

TABLE 2. ESTIMATED CHROMIUM CONCENTRATION OF PUMPED WASTEWATER

Well	Estimated Pumping Rate (gpm)	Estimated Pumping Duration (hours)	Volume (gallons)	Volume (liters)	Reported Chromium Concentration (µg/L)	Mass of Chromium in Pumped Water (milligrams)	Notes
Ogallala Wells							
WMW-02A	3	2	360	1,361	22.4	30.5	
WMW-03A	3	2	360	1,361	6	8.2	
WMW-05A	3	1	180	680	464	315.7	
WMW-06A	3	2	360	1,361	80.5	109.5	
WMW-15A	3	2	360	1,361	9	12.2	
WMW-17A	3	1.5	270	1,021	65	66.3	
WMW-24A	3	1.5	270	1,021	140	142.9	
WMW-27A	3	1	180	680	379	257.9	
WMW-34A	3	2	360	1,361	34	46.3	
WMW-37A	3	1.5	270	1,021	<10	5.1	
TCEQ-MW-02	3	3	540	2,041	2,840	5,797	
Edwards-Trinity Wells							
WMW-05B	0.25	3	45	170	442	75.2	
WMW-11B	0.25	3	45	170	54.8	9.3	
WMW-21B	0.25	3	45	170	15.5	2.6	
WMW-32B	0.25	3	45	170	21.9	3.7	
		Total Volume (liters) =		**9,185**	**Total Mass (milligrams) =**	**6,418.6**	**Mixed Concentration (µg/L) = 698.8**

NOTE:
gpm = gallon(s) per minute
µg/L = microgram(s) per liter

Figures



Remedial Investigation/ Feasibility Study
West County Road 112 Ground Water Plume Site
Midland County, Texas

Figure 1
Site Layout

2012 -11-14 R:\Federal\EPA\RAC II\0065-West County Road 112\GIS\MXDs\SAP_Figures\FigureXX_SiteLayout.mxd EA-Dallas jschwertz

M:/PROJECTS/EPA_RAC/EPA6.14_WEST COUNTY RD 112/GIS/MXDS/BASE_MAPS/MONITORING_WELL_LOC_MAP.MXD 116250

N

0 500 1000 Feet

Explanation

- EPA monitoring well
- Schlumberger monitoring well
- Lear monitoring well
- TCEQ monitoring well

WMW-15 Well designation

EA ENGINEERING, SCIENCE, AND TECHNOLOGY, INC.

WEST COUNTY ROAD 112
GROUND WATER PLUME SITE
MIDLAND COUNTY, TEXAS

Monitoring Well Locations

DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	DATE	PROJECT NO	FIGURE
DWR	CRS	DWR	1:12,000	10/31/2012	1434265	2

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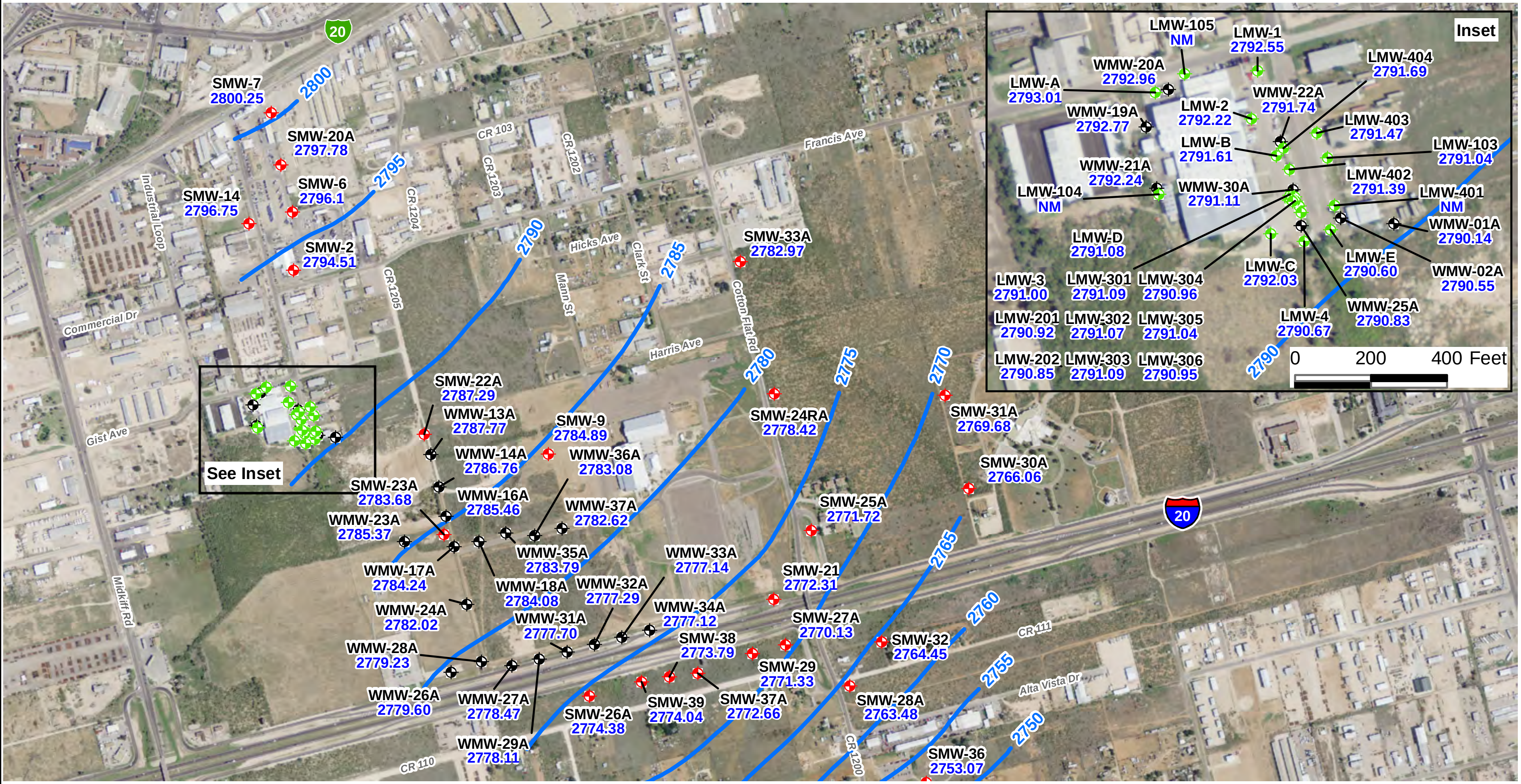

N

0 600 1200 Feet

Explanation

- EPA monitoring well
- Lear monitoring well
- Schlumberger monitoring well
- Ground water elevation (dashed where inferred)

WMW-02A Well designation
2790.55 Ground water elevation, feet above mean sea level

EA ENGINEERING, SCIENCE, AND TECHNOLOGY, INC.

WEST COUNTY ROAD 112
GROUND WATER PLUME SITE
MIDLAND COUNTY, TEXAS

Ground Water Elevations in the Ogallala Aquifer June 2012

DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	DATE	PROJECT NO	FIGURE
DWR	CRS	DWR	1:14,400	10/23/2012	1434265 B 1	3

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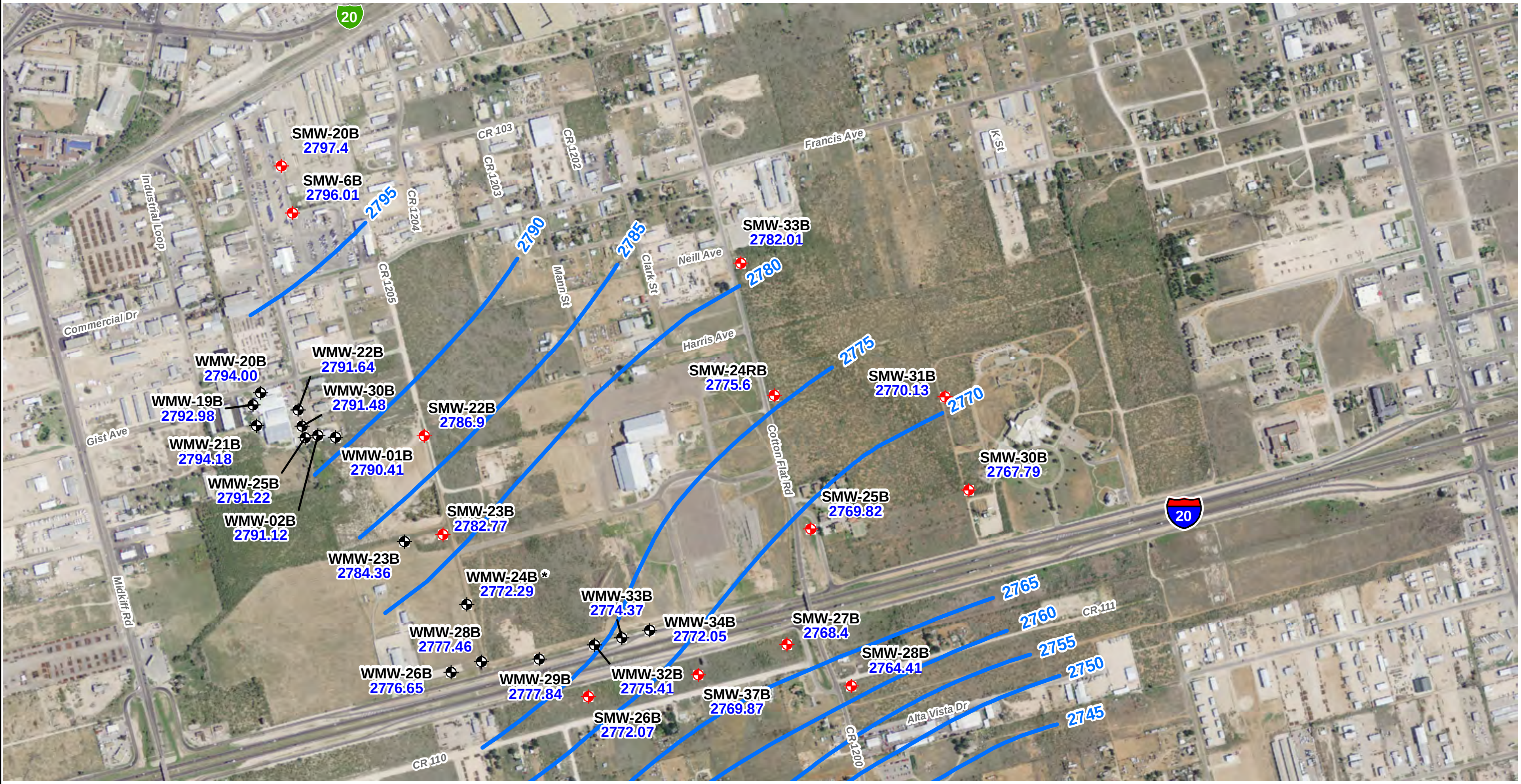

N

0 600 1200 Feet

Explanation

EPA monitoring well

Schlumberger monitoring well

Ground water elevation (dashed where inferred)

WMW-02B Well designation

2791.12 Ground water elevation, feet above mean sea level

Note: * not used for contouring

EA ENGINEERING, SCIENCE, AND TECHNOLOGY, INC.

WEST COUNTY ROAD 112
GROUND WATER PLUME SITE
MIDLAND COUNTY, TEXAS

Ground Water Elevations in the Trinity Aquifer June 2012

DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	DATE	PROJECT NO	FIGURE
DWR	CRS	DWR	1:14,400	10/23/2012	1434265 B 1	4

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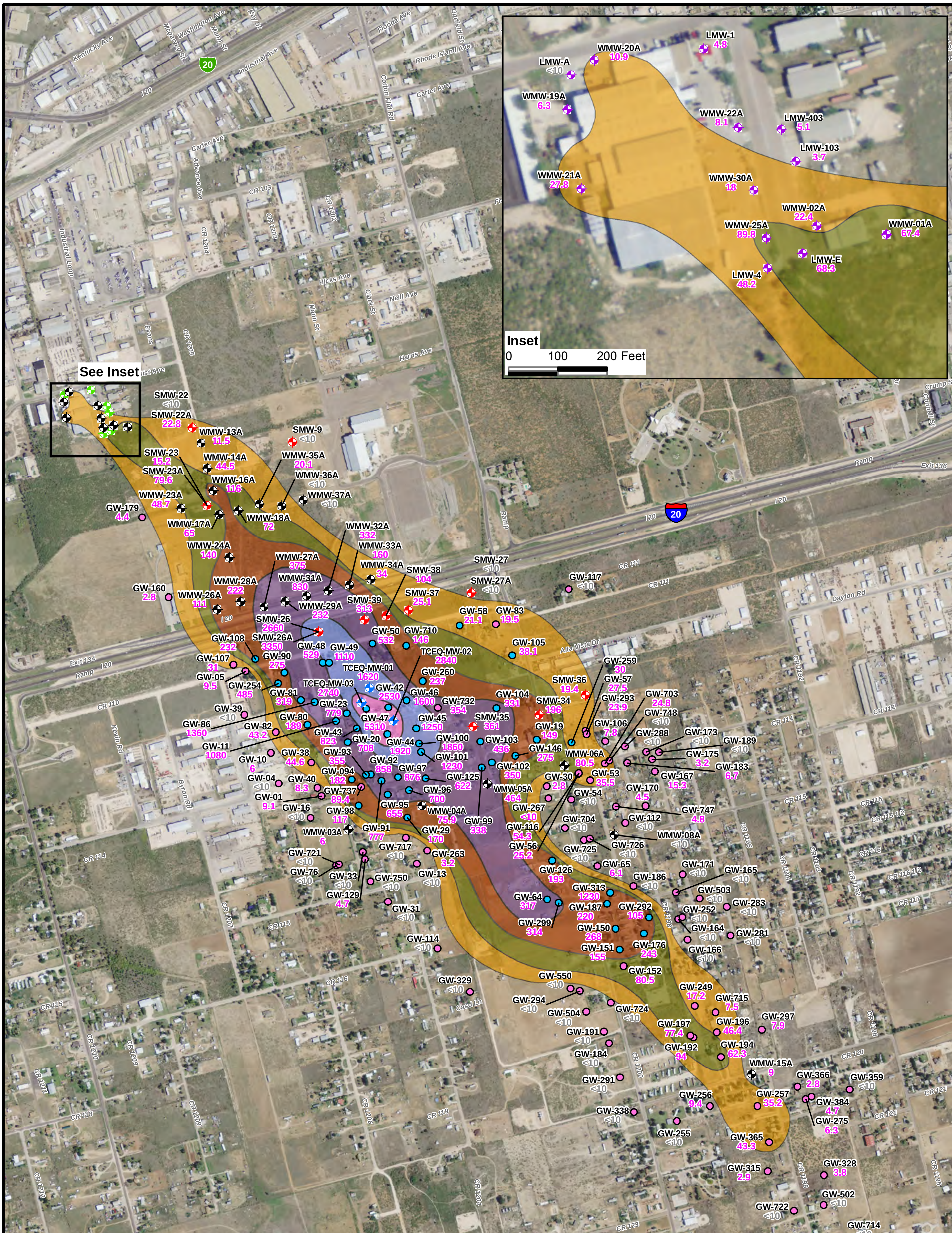


N

0 500 1000 Feet

Explanation

- EPA monitoring well
- Lear monitoring well
- Schlumberger monitoring well
- TCEQ monitoring well
- Sample location
- Sample location with filtration system
- WMW-15A Well designation
- 9 Total Chromium (Cr) concentration micrograms per liter (µg/L)
- <10 Below reporting limit
- Total Cr above 10 µg/L
- Total Cr above 50 µg/L
- Total Cr above 100 µg/L
- Total Cr above 300 µg/L
- Total Cr above 1,250 µg/L
- Total Cr above 2,500 µg/L

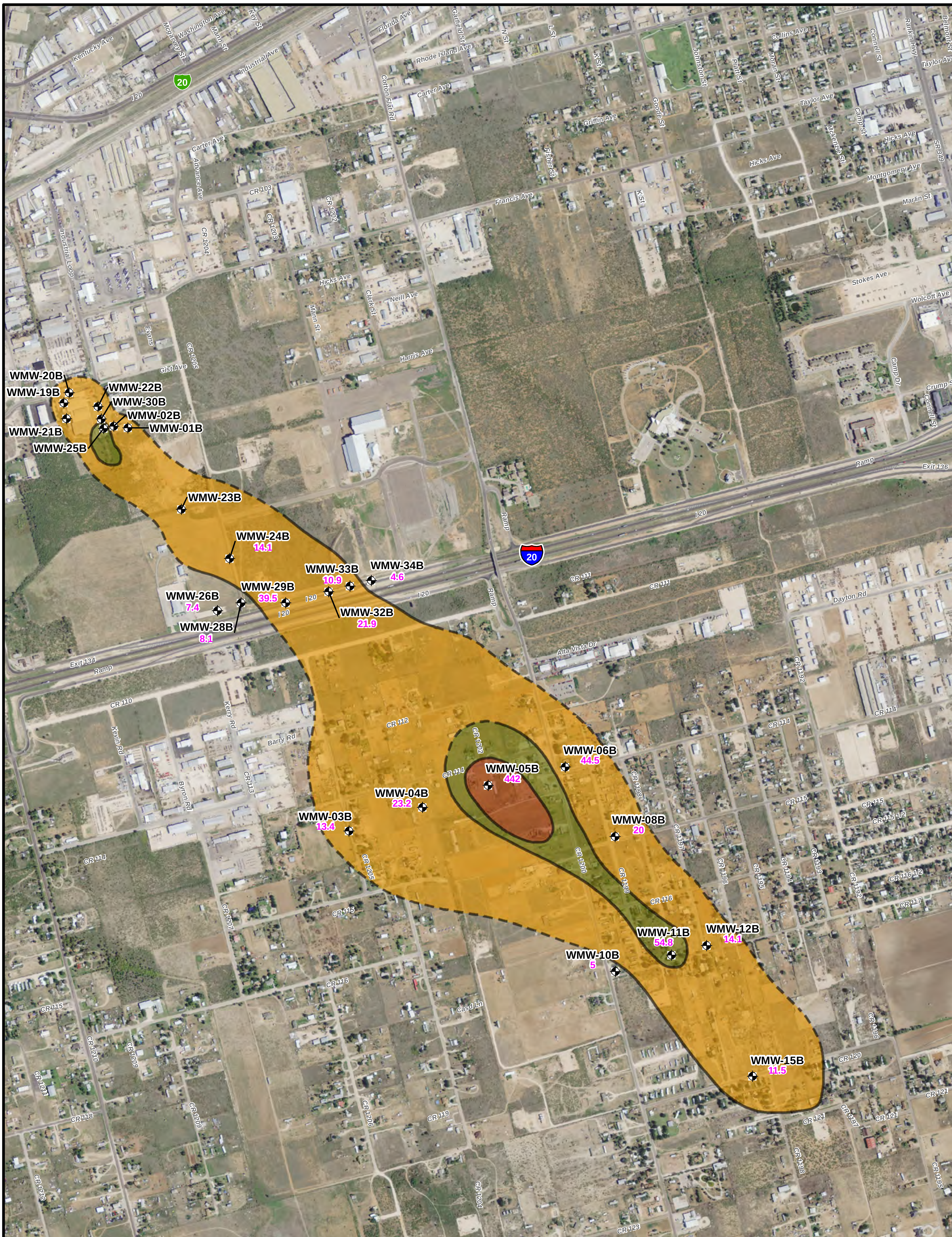
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

EA ENGINEERING, SCIENCE, AND TECHNOLOGY, INC.

WEST COUNTY ROAD 112
GROUND WATER PLUME SITE
MIDLAND COUNTY, TEXAS

Concentrations of Total Chromium in Ground Water Ogallala (Shallow Zone) Aquifer June - August 2012

DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	DATE	PROJECT NO	FIGURE
DWR	CRS	DWR	1:12,000	10/31/2012	1434265	5



N

0 500 1000 Feet

Explanation

EPA monitoring well

WMW-15B Well designation

11.5 Total Chromium concentration (µg/L)

Total Chromium (Cr) above 10 micrograms per liter (µg/L)

Total Cr above 50 µg/L

Total Cr above 100 µg/L
(dashed where inferred)

Note: Data from 2012 posted; remaining plume inferred from 2011 data.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

EA ENGINEERING, SCIENCE, AND TECHNOLOGY, INC.

WEST COUNTY ROAD 112
GROUND WATER PLUME SITE
MIDLAND COUNTY, TEXAS

Concentrations of Total Chromium in Ground Water Edwards-Trinity (Deep Zone) Aquifer January and June 2012

DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	DATE	PROJECT NO	FIGURE
DWR	CRS	DWR	1:12,000	2/22/2013	1434265	6

Appendix A

Forms

FIELD DATA SHEET
SINGLE-WELL RECOVERY TESTING
WEST COUNTY ROAD 112 GROUND WATER PLUME, MIDLAND COUNTY, TEXAS

Date: ______________________________

Pumping Well = ________________			Totalizing Meter Reading (gallons)	Comments/Notes (Critical: Note time pump on/pump off)
Time	Discharge (sec/5 gal)	Depth to Water (feet btoc)		

CALCULATION FOR ESTIMATED CHROMIUM CONCENTRATION OF PUMPED WASTEWATER
WEST COUNTY ROAD 112 GROUND WATER PLUME, MIDLAND COUNTY, TEXAS

Well	Pumping Rate (gal/min)	Pumping Duration (hr)	Volume (gal) (rate * duration * 60)	Volume (L) (volume in gal * 3.78)	Reported Chromium Concentration (µg/L)	Mass of Chromium in Pumped Water (mg) (volume in L * conc /100)	Notes
Ogallala Wells							
WMW-02A					22.4		
WMW-03A					6		
WMW-05A					464		
WMW-06A					80.5		
WMW-15A					9		
WMW-17A					65		
WMW-24A					140		
WMW-27A					379		
WMW-34A					34		
WMW-37A					<10		
TCEQ-MW-02					2,840		
Edwards-Trinity Wells							
WMW-05B					442		
WMW-11B					54.8		
WMW-21B					15.5		
WMW-32B					21.9		
			Total Volume (L) =		**Total Mass (mg) =**		
			Mixed Concentration (µg/L) (Total Mass/Total Volume*1000) =				

Notes:

conc = concentration
gal = gallon(s)
hr = hour(s)
L = liter(s)
mg = milligram(s)
min = minute(s)
µg/L = microgram(s) per liter

Additional Field Notes:

____
____
____
____
____
____

Appendix B

Standard Operating Procedures

Standard Operating Procedure No. 013
for
Collection of Monitoring Well Samples

Prepared by

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Hunt Valley, Maryland 21031

Revision 0
August 2007

CONTENTS

1. SCOPE AND APPLICATION

The purpose of this Standard Operating Procedure is to delineate protocols for the collection of groundwater samples from monitoring wells.

2. MATERIALS

The following materials may be required:

0.45 µM filters	Polyvinyl chloride bailer (for purging only)
Bladder pump (dedicated to one well only)	Sample bottles and labels
Conductivity meter	Stainless steel bailer (for purging and sampling)
Dissolved oxygen meter	Submersible pump and hose (for purging only)
Generator	Thermometer (optional)[1]
Logbook or book of field parameter forms	Transparent bailer with a double check valve
Peristaltic pump with tubing for filtering samples	Turbidity meter
pH meter with oxidation-reduction potential probe	Tygon tubing
Photoionization detector organic vapor analyzer.	Variable speed, low flow submersible pump (e.g., Grundfos MP1 groundwater sampling pump) (for purging and sampling)
Plastic sheeting	Water level indicator
Polypropylene rope	
Polytetrafluoroethelyne (PTFE) bailer with PTFE-coated stainless steel cable, double check valve top, and controlled flow bottom discharge attachment[2] for volatile organic compound (VOC) sampling (40-mL vials), and top discharge attachment for collecting larger samples (1-L bottles) (for purging and sampling)	

3. PROCEDURE

3.1 GENERAL

Groundwater sampling will follow these general steps:

- Arrive onsite
- Set up apparatus (generators, pumps, etc.)
- Glove
- Organic vapor check, water level, and well depth measurements

1. Temperature compensation and measurement capabilities are generally available as integral functions of pH meters and conductivity meters. If this is the case, a separate thermometer is not required.
2. Although use of a controlled flow bottom discharge valve is historically preferred, use of such a device can cause aeration of the sample.

- Sample non-aqueous phase liquids (NAPLs) (as required)

- Begin purge procedure

  — If using bailer to purge and sample, see Section 3.6
  — If using pump to purge and bailer to sample, see Section 3.7
  — If using bladder or low-flow pump to purge and sample, see Section 3.8

- Decontaminate/reglove

- Take samples

  — If with bailer, see Section 3.6
  — If with bladder or low flow pumps, see Section 3.8

- Decontaminate/dispose of wastes, move equipment to next site.

3.2 GENERAL RULES FOR GROUNDWATER FIELD PARAMETER LOGBOOK

Only one site or installation per logbook, and only one sampling location per page or form (if using pre-printed forms). The same book may be used for more than one sampling event. First five pages will be reserved for index, general notes, etc. Sign and date each entry. Last five pages will be reserved for recording calibration data for the pH, temperature, turbidity, oxidation-reduction potential, dissolved oxygen, and conductivity meters. Use the page number or a separately recorded “Cal Reference Number” to refer to each calibration. As appropriate, insert the cardboard flap under the form being filled out, so that writing does not go through to the pages below. As appropriate, fill in the forms from front to back of the logbook, tearing out the white copy for each sample when the sample has been collected. This copy goes in the cooler with the sample, directly to the laboratory. The original copy must be torn out before you write on the back of the duplicate form. As appropriate, duplicate copies, index pages, and calibration sheets remain intact.

3.3 GROUNDWATER SAMPLING GENERAL RULES

Groundwater samples will be collected from the least contaminated wells first, progressing to the most contaminated[3]. Upon arrival at the well site, immediately set up and organize the purging, sampling, and filtration equipment. If needed, due to muddy or contaminated ground, remoteness from sampling vehicle, and\or for placement of hose(s) and\or power cord if a pump is used, place clean plastic sheeting at, or around the well, to serve as a clean staging area for purging and sampling equipment, as conditions warrant. Care must be exercised not to step on plastic sheeting. If the well is remote from the sampling vehicle, set up the filtration equipment

3. First round samples are to be collected from upgradient wells first, moving to downgradient wells under the assumption that upgradient wells will be less contaminated than downgradient wells. Results of first round analysis may mandate a change in sampling sequence.

and place rope, wrapped bailer, and pre-labeled sample containers on the plastic sheet, from the well. When a pump is to be used, situate the portable generator on level ground approximately 15 ft away from and downwind from the well. All generator maintenance (oil and fueling) is to be performed offsite. If the hose(s) and/or power cord of the pump are not on a reel, place the pump with its hose and power cord on the plastic sheeting downhill from the well.

Check well headspace for organic vapor which may pose a health and safety hazard and indicate the presence of NAPL. Measure depth(s) to and thickness(es) of NAPL(s) as appropriate. Measure the depth to water and depth of well. From the water depth, well diameter, sand pack length, etc., calculate the equivalent volume (1 EV) of water in the well.

1 EV = volume in casing + volume in saturated sand pack. Therefore, if the water table lies below the top of the sandpack, use the following equation:

$$1\ \text{EV} = (\pi R_w^2 h_w) + (0.30\pi(R_s^2 - R_w^2)h_w) * (0.0043)$$

If the water table lies above the top of the sandpack use this equation:

$$1\ \text{EV} = [(\pi R_w^2 h_w) + (0.30\pi(R_s^2 - R_w^2)h_s)] * (0.0043)$$

where

R_s = Radius of sandpack in inches
R_w = Radius of well casing in inches
h_s = Height of sandpack in inches
h_w = Water depth in inches

0.0043 gal/in.^{3}
Assumed filter pack porosity = 30 percent.

Samples will always be collected in order of decreasing volatility (i.e., the samples to be analyzed for the volatile constituents should be collected first). Deliver the VOC sample to the vial by allowing the water to trickle down the inside wall of the vial at a rate no greater than approximately 100 ml/min. Other samples may be delivered at a faster rate. Sampling rates will at no time exceed 1 L/min. Procedures for each class of samples are contained in the site-specific Quality Assurance Project Plan.

When collecting samples for volatile analysis, care should be taken to prevent analyte loss by volatilization. The following procedures should be adhered to when collecting these samples:

- Avoid excessive aeration and agitation of sample.

- Fill vial so that a reverse meniscus is present by adjusting the flow rate from the sampling device.

- Place septum on vial so that the PTFE side is in contact with the sample. After the cap is on the bottle, check for air bubbles in the sample. If air bubbles are present, properly dispose of that sample and recollect the sample in the same vial.

- Make sure vial is labeled and immediately transfer the vial to the cooler with ice.

Filtered and unfiltered samples will be taken for inorganics (metals) analyses. The samples will be filtered through an in-line 0.45-µM filter (preferred method), or by gravity through a 0.45-µM membrane placed in a filter funnel. Use forceps to place the membrane into the funnel and pour sample through funnel until appropriate volumes have been filtered.

If necessary, due to slow filtering, a peristaltic pump may be used to filter the sample through an in-line filter. Connect the pump to the generator, attach tygon tubing to the bottom discharge valve on the bailer. Start pump and collect sample from the end of the in-line filter directly into the proper container, preserved, and placed in the cooler. Filtered samples will be preserved in the field with acid to a pH of less than 2. Make sure sample bottle is labeled and the cap is on tightly. Then place in cooler with ice immediately.

— OR —

If a low flow pump is used collect the samples, filtered samples will be taken by installing a 0.45-µM filter in-line and pumping the water through the filter. Collect sample from the end of the in-line filter directly into the proper container, preserved, and placed in the cooler. Filtered samples will be preserved in the field with acid to a pH of less than 2. Make sure sample bottle is labeled and the cap is on tightly. Then place in cooler with ice immediately.

Unfiltered samples will be collected by slowly pouring the sample water into the appropriate sample container, being careful not to agitate or cause bubbles to form. Do not overfill bottles. Make sure sample bottle is labeled and the cap is on tightly, then place the sample in cooler with ice immediately.

All samples will be delivered to the laboratory as soon as possible. If possible, samples will be shipped on the same day as they are collected. If samples must be retained due to weekend sampling (Friday through Sunday), the laboratory will be notified as to the time sensitive nature of the samples.

3.4 SAMPLING OF NON-AQUEOUS PHASE LIQUIDS

If NAPLs are detected in the well, a sample from all layers must be collected prior to any purging activities. NAPLs may be indicated by the presence of volatiles in the well headspace, and confirmed by the oil/water interface probe.

Collecting light non-aqueous phase liquid (LNAPL) will be accomplished using a transparent bailer with a double check valve. This bailer will be slowly lowered until the bottom of the bailer is 1-2 in. below the LNAPL-water interface, then slowly withdrawn. Verify that the interface was sampled by visual inspection of the bailer contents through the side of the bailer. Measure the thickness of the LNAPL in the bailer and note in the Field Logbook. Sample for laboratory analysis. An additional field verification may be performed by decanting the remainder of the contents of the bailer into a glass jar, adding a hydrophobic dye such as Sudan IV, or Redoil, shaking the sample and looking for coloration of NAPL. Alternate field tests are: examine the sample under ultraviolet light (many fluoresce), or allow the sample to stand overnight, and examine for interface and/or volatiles in the headspace the following day. Refer to following sections on purging and sample collection for setup and general operation.

Collecting dense non-aqueous phase liquids (DNAPLs) will be accomplished using a transparent bailer with a double check valve. The bailer must be lowered very slowly to the bottom of the well and raised slowly out of the well in a controlled fashion. Sample for analysis as above. The same field check described above may be employed for DNAPL. Refer to following sections on purging and sample collection for set up and general operation.

If NAPLs are present in the well, **and** a low-flow pump is to be used for purging and sampling, the well will be allowed to re-equilibrate prior to purging and sampling. This will be accomplished by allowing the well to stand undisturbed for at least 8 hours prior to purging and sample collection.

3.5 WELL PURGING GENERAL RULES

Water within the casing of a well will stagnate, degas, lose volatiles, possibly precipitate metals due to changes in redox potential, and may react with the screen and/or casing material. It is, therefore, necessary to purge a sufficient volume of this stagnant water from the well and/or casing to ensure that a representative sample of formation water can be obtained. Traditionally, the volume of water to be purged was arbitrarily set at 3-5 equivalent volumes. Recent advances in sampling technologies have caused a re-thinking of such arbitrary purge volumes. It is for this reason that monitoring of select chemical and physical properties of the sample medium will be used instead of strict volumes to determine when a representative sample may be taken from a well.

Acceptable purge/sampling devices include: bailers, high-discharge submersible pumps (purge only), and variable speed, low-flow pumps which include both submersible pumps (purge and sample) and dedicated bladder pumps (purge and sampling). It is recommended to purge and sample at similar rates with one type device per well. An acceptable exception to this general rule is to use a high-discharge submersible pump to purge a deep, fast-recharging well, and a bailer to sample the same well.

Peristaltic, gas-lift, and centrifugal pumps can cause volatilization, produce high pressure differentials, and can result in variability in the analysis of some analytes of interest.
These types of pumps will not be used to purge or sample wells.

To prevent groundwater from cascading down the sides of the screen into an open hole, thereby aerating the sample, purge rates will closely match recharge rates. If the static water level is within the casing, the initial purge rates may be set high enough to lower the water level to the top of the screen, then reduced to maintain that level.

Purging will be accomplished with either a submersible pump, a low-flow (submersible or bladder) pump, or bailer. The choice of bailer or pump will be based on depth to water table, volume to be purged, and permeability of the aquifer. If the well recharges rapidly and/or has greater than 20 gal (estimated EV) to be purged, water may be removed with a submersible pump or a low-flow pump. If the well recharges slowly and/or has less than 20 gal to be purged, water will be removed with a bailer or a low-flow pump.

Purging will be accomplished with as minimal disturbance to the surrounding formation as possible.

Purge water will be containerized onsite until analysis of samples is completed. Based on sample results, accumulated purge water will be properly disposed.

If the water level is within the screened interval and the well recharge rate is less than 0.1 L/min, purge the well using a low-flow pump as follows:

1. Draw the water down to within 1 ft of the top of the pump.
2. Allow the well to recover.
3. Check and record field parameters.
4. Repeat Steps 1 through 3 then collect samples for metals analysis only[4].
5. Note the event in the Field Logbook, and report the problem to the Project Manager. If this extremely low recharge problem consistently occurs in a given well, the well may be considered for re-development and/or replacement.
6. If adjacent wells have elevated VOC levels, additional soil gas surveys will be considered in the vicinity of the low recharge well to help determine the need for replacement.

3.6 PURGING AND SAMPLING WITH BAILERS

Bailers may be used for both purging and sampling wells if: (a) the well recharge rate is less than 4 L/min, (b) depth to the water table is less than 50 ft, and (c) less than 20 gal are to be purged (5 EV < 20 gal)[5].

4. Analyte losses due to volatilization in a drained well are too high for valid VOC sampling (McAlary and Barker 1987).

When purging with a bailer, either a polyvinyl chloride, PTFE, or stainless steel bailer may be used. The bailer will be attached to either a spool of PTFE-coated stainless steel cable or polypropylene rope. If using cable, attach it to the bailer using stainless steel cable clamps. Thoroughly decontaminate the cable after each use, prior to rewinding cable onto spool. Cable clamps and raw cable ends may serve to trap contamination. Exercise particular caution in decontaminating these areas. If using rope, attach the rope to the bailer using a bowline knot, dispense the needed length (a few feet more than the well depth) and cut the remainder away; then, at the end opposite the bailer, make a slip knot and place it around the well casing or protective posts to prevent losing the bailer and rope down the well. The polypropylene rope will be not reused; it will be properly disposed of. Either type of bailer will be repeatedly lowered gently into the well until it fills with water, removed, and the water will be discharged into an appropriate container until purging is complete. Care must be taken not to unduly agitate the water, as this tends to aerate the sample, increase turbidity, makes stabilization of required parameters difficult to achieve, and generally prolongs purging.

After purging 2 EV, obtain a sample of groundwater and measure the following stabilization parameters: temperature, conductivity, pH, turbidity, redox potential (Eh), and dissolved oxygen level at each successive half-well volume. When three of these stabilization parameters are in agreement within approximately 10 percent in three consecutive half-well volume samples, sufficient water has been purged from the well. The results of these tests should be recorded in the sampling logbook. Should these parameters not reach agreement, no more than five well volumes will be purged.

Immediately upon completion of purging, collect samples for laboratory analysis using a PTFE bailer on a PTFE-coated stainless steel cable. The bailer will be equipped with double check valve top and controlled flow bottom discharge attachments for VOC sampling (40-mL vials), and top discharge attachment for collecting larger samples (1-L bottles).

Slowly, so as not to agitate the water, lower the bailer into the well, using a spool of PTFE-coated cable. Allow bailer to fill, withdraw smoothly. Refill bailer as needed.

If the controlled flow bottom discharge attachment is used for VOC sampling, attach it to the bottom of the bailer. Using the stopcock valve on the bailer to control the flow, fill sample vials as described above in Section 3.3.

Remove check valve top and pour unfiltered sample into inorganics sample bottles.

Collect filtered samples as described in Section 3.3. Decontaminate bailer and cable.

5. These numbers are based on the following assumptions: (1) In purging, it is preferable to remove water at approximately the recharge rate; (2) 4 L/min is estimated as the approximate maximum rate at which water can be removed with a bailer from depths of 20-50 ft; and (3) 20 gal is estimated to be at the limit of the sampler's endurance, at which point fatigue and sloppiness of technique begin.

3.7 PURGING WITH PUMP, SAMPLING WITH BAILER

If the recharge rate of the well is greater than 30 L/min, or the water level is deeper than 50 ft, or more than 20 gal of purge water will be generated (5 EV > 20 gal), then purging and sampling may be accomplished using a submersible pump/bailer combination.

When purging with a pump, gradually lower the intake until it is submerged within the screened interval. Lower an electronic water level probe to the top of the screen (as determined from completion records) to the monitor water level, start pump, and slowly lower the pump as the water level continues to fall. Care should be exercised to lower the water column to the top of the screened interval (water level probe will stop beeping) but not below the top of the screen if possible. This will ensure that the stagnant layer has been removed, but should minimize the detrimental effects of over pumping the well. Secure hose(s) and/or power cord to casing and place discharge hose into the proper container, downhill and as far away from the well as possible. Determine and record the discharge rate.

Discharge rate = volume of container/time to fill container

The discharge rate will be established at approximately equal to or just greater than the well's recharge rate (determined from well development). If well development records are incomplete, recharge rate can be determined by monitoring the rise/fall of the water level within the casing as one purges the well. If the water level is static at a given pumping rate, but fluctuates up or down as pumping rate is decreased or increased, the pumping rate at which the water level is static is the recharge rate.

After purging 2 EV, obtain a sample of groundwater and measure the following stabilization parameters: temperature, conductivity, pH, turbidity, redox potential (Eh), and dissolved oxygen level at each successive half-well volume. When three of these stabilization parameters are in agreement within approximately 10 percent in three consecutive half-well volume samples, sufficient water has been purged from the well. The results of these tests should be recorded in the sampling logbook. Should these parameters not reach agreement, no more than five well volumes will be purged.

Immediately upon completion of purging, collect samples for laboratory analysis using a PTFE bailer on a PTFE-coated stainless steel cable. The bailer will be equipped with double check valve top and controlled flow bottom discharge attachments for VOC sampling (40-mL vials), and top discharge attachment for collecting larger samples (1-L bottles). Filtration of metals samples will be accomplished using either an in-line filter attached to the bottom of the bailer, or a funnel and appropriate filter (Section 3.3).

Slowly, so as not to agitate the water, lower the bailer into the well, using a spool of PTFE-coated cable. Allow bailer to fill, withdraw smoothly, fill sample containers as described in Section 3.6. Decontaminate bailer and cable in and decontaminate pump.

3.8 PURGING AND SAMPLING WITH LOW-FLOW PUMP

To obtain representative samples, subsurface disturbances should be kept to a minimum, thereby preventing sample alteration due to sampling actions. The reasoning behind the use of low-flow pumps to purge and sample monitoring wells is that these pumps minimize physical disturbance (turbulence) at the sampling point and chemical changes (aeration) in the medium. For these reasons, the low-flow pump is the preferred method for both purging and sampling in most cases. For the purposes of this SOP, "low-flow pumps" are defined as either dedicated bladder pumps or variable speed submersible pumps. Practical operational flow rates for these sampling devices range from 0.1 L/min to 30 L/min.

Low-flow pumps may be used for purging and sampling any well having recharge greater than 0.1 L/min, which is the practical lower limit of pump performance. Below that pumping rate, pump inefficiencies and/or overheating may alter the physical and chemical properties of the sample. If the pump is continuously operated at sampling rates higher than the well recharge rate, the water level will be lowered in the well, possibly allowing aeration of the sample which is unacceptable sampling procedure. Low-flow pumps are suitable for sampling wells with recharge rates lower than 0.1 L/min if precautions are taken to avoid aeration of the sample.

Low flow submersible pumps will be used as follows:

- Lower the pump into the well, slowly so as not to agitate the water, until the pump is at the mid-point of the screened interval or the mid-point of the water column if the static water table lies below the top of the screen[6]

- Attach the pump's umbilical cord (which will consist of power cord and sampling tubing) to the protective casing, or lock the cord spool so that the pump cannot move vertically in the well during sampling.

- Lower the water level probe into the well behind the pump until it just touches water. This will allow the sampler to monitor the water level while purging and sampling, and prevent the inadvertent drying of the well.

6. This assumes a 10-ft screened interval. If the screened interval is greater than 10 ft, multiple samples should be taken as follows:
   - If the screen is 10-12 ft, sample the canter of the water column, as outlined above.
   - If the screen is longer than 12 ft, and the water column is 10 ft or less, sample the center of the water column.
   - If the screen is longer than 12 ft, and the water column fills the screen, or extends above the screen, sample at 1/3 and 2/3 the height of the water column, or about every 6 ft.

- Begin purging at the pump's lowest setting, then gradually increase rate[7] until the pumping rate matches the aquifer recharge rate. **If the water level is above the top of the screen**, the pumping rate may be allowed to slightly exceed recharge rate, lowering the water level to no less than 1 ft above the screen, then reduced until it matches recharge rate and purging continued. **If the water level is below the top of the screen**, always keep the purge rate lower than well's recharge rate.

- Monitor stabilization parameters listed in Section 3.6 beginning immediately, using an in-line monitoring system. Record parameters regularly, at a rate of one set of parameters per each 1-3 liters of water removed from the well. When these parameters stabilize to within 10 percent over three consecutive readings, reduce[8] flow rate to 0.1 L/min (if needed) and begin collecting VOC samples directly from the discharge line.

- If the well recharges at a rate less than 0.1 L/min, purge until the water level is even with the top of the screen, allow the well to recover, and sample immediately.

- Remove and decontaminate water level probe and pump.

4. MAINTENANCE

Refer to manufacturer's requirements for maintenance of pumps and generators.

5. PRECAUTIONS

Refer to the site-specific Health and Safety Plan for appropriate personal protective equipment.

6. REFERENCES

Garske, E.E. and M.R. Schock. 1986. An Inexpensive Flow-Through Cell and Measurement System for Monitoring Selected Chemical Parameters in Groundwater.

Gass, T.E., J.F. Barker, R. Dickhout, and J.S. Fyfe. 1991. Test Results of the Grundfos Groundwater Sampling Pump, in Proceedings of the Fifth National Symposium on Aquifer Restoration and Groundwater Monitoring.

7. Some sources indicate that the pumping rate should not exceed 1 L/min, with 0.5 L/min being preferable. The optimal purge rate is highly aquifer dependent, and may range from less than 0.5 L/min to greater than 10 L/min. The purge rate for a given well will, therefore, be a field decision, based on well development, purge, and sampling records rather than SOP mandate.
8. Sampling should occur at the same rate as purging as long as aeration of sample does not occur.

McAlary, T. A. and J.F. Barker. 1987. Volatilization Losses of Organics During Groundwater Sampling From Low Permeability Materials, in Groundwater Monitoring Review. Fall.

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Standard Operating Procedure No. 033
for
Aquifer (Hydraulic) Testing

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1. SCOPE AND APPLICATION

The purpose of this Standard Operating Procedure (SOP) is to define various hydraulic test methods which may be used, to specify how these tests are to be performed, and to provide appropriate methodologies for data reduction and interpretation. This SOP assumes a high degree of technical competency on the part of the investigator, in that certain assumptions and interpretations must be made in the selection of the test and data analysis to achieve valid results.

Aquifer testing is a process performed on selected wells to characterize the **Hydraulic Conductivity**, **Transmissivity**, and **Storativity** of the aquifer into which those wells are installed. Aquifer tests fall into two broad categories: pumping tests and slug tests. Pumping tests and slug tests are relatively inexpensive when compared to the remedial investigation budget as a whole, but it should be noted that, as with many *in situ* tests, aquifer tests may yield non-unique solutions.

Pumping tests are typically performed on wells installed in highly permeable materials, confined aquifers, and in areas of little or no suspected contamination in the groundwater. The principle of pumping tests is to remove water from the aquifer at a sufficient rate and for a sufficiently long period of time to stress the aquifer and cause measurable drawdown in the pumped well and adjacent (10 to several hundreds of feet) observation well(s). The aquifer characteristics can then be calculated by substituting inter-well distances, drawdown and well discharge data into appropriate equations, employing curve matching techniques, or using computer programs to reduce the data.

- Advantages of performing pumping tests are: (1) they encompass large areas, (2) test results are more accurate, (3) they can resolve complex aquifer conditions (e.g., boundaries), (4) time periods and pump rates can be varied, and (5) pumping tests represent remedial actions.

- Disadvantages of pumping tests are: (1) large quantities of potentially contaminated water are generated, (2) the contaminant plume may be moved by the test, (3) they are very costly, and (4) the data produced are averages over large areas.

Single-Well Permeability Tests (Slug Tests) are conducted to determine the characteristics of an aquifer in materials whose conductivity is too low to perform a pumping test, or in aquifers which are highly contaminated. Slug tests consist of inserting and/or removing either a slug of inert material of known volume, or a “slug” of water of known volume. Either method will cause an instantaneous rise or fall and subsequent recovery of the water table within the aquifer.

- Advantages of slug tests are: (1) they provide location-specific data, (2) they are small-scale and unlikely to move the contaminant plume, (3) no contaminated water (other than decontaminated solutions) is generated, (4) they are low cost, therefore (5) high data density is feasible, and (6) they can be used as an aid in selecting an appropriate area to perform pumping test(s).

- Disadvantages of performing slug tests are: (1) they provide less precise estimates of parameters; (2) they may not yield values for storativity; (3) they cannot resolve complex geometries; and (4) since they are short-term tests, they cannot resolve long-term events.

2. MATERIALS

2.1 ALL TESTS

The following materials may be required for all tests:

Copy of the site Health and Safety Plan	Health and Safety monitoring equipment, and personal protective equipment as required by the Health and Safety Plan
Calculator	Portable computer[1]
Containers for investigation-derived materials	Program diskettes
Data diskettes	Stopwatches
Decontamination equipment and supplies	

2.2 PUMPING TESTS

The following materials may be required for pumping tests:

Generators (2), fuel, extension cords and/or other source of onsite electrical power	Stainless steel submersible pump with associated tubing, clamps, and wiring
Logbook	Steel register flowmeter or stopwatch and bucket, graduated cylinder, or rain gauge
Pump	Transducer or other water level indicator[1]
Recording barometer or other source of local barometric readings (e.g., local airport or National Weather Service recording station)	Type curves for curve-matching analyses
Semilogarithmic paper-arithmetic vertical scale and logarithmic horizontal scale, or log-log paper	

2.3 SLUG TESTS

The following materials may be required for slug tests:

1. Although removal (or insertion) of larger volumes of water may increase the recovery time(s) of the aquifer to the point that use of electrical water level meters or steel tapes is feasible, piezometers and data loggers are preferred because they tend to provide more complete records with less maintenance and operator error.

Test Conducted with Inert Cylinder	
Transducer[2]	Inert, negatively buoyant cylinder of known volume
Logbook and/or field data sheets (examples provided in SOP No. 016)	Type curves for curve-matching analyses
Semilogarithmic paper-arithmetic vertical scale and logarithmic horizontal scale	Slug device (solid stainless steel or a sealed polvyinyl chloride cylinder filled with sand or similar material)
Test Conducted with Input/Output of Water	
Teflon bailer with Teflon-coated stainless steel leader and rope or pump	
— OR —	
Stainless-steel submersible pump or centrifugal pump	Pump wiring
Teflon or polyethylene flexible piping	Steel register flowmeter
Generator and fuel or other onsite source of electricity	American Society for Testing and Materials (ASTM) Type II water
Stainless-steel hose clamps	
— AND —	
Logbook	Type curves for curve-matching analyses
Semilogarithmic paper	Approved water and/or containers for removed water as required in SOP No. 042
Transducer or other water level indicator[1]	

3. PROCEDURE

Regardless of the test method chosen, the following general procedures must be considered:

- All well intrusive equipment must be decontaminated prior to and after use.
- All water removed from the test wells is considered, and must be treated, as purge water.
- The accuracy of the reading(s) from pressure transducer (piezometer) and data logger output should be verified prior to beginning any test, periodically during the test, and immediately after the test by measuring the groundwater level with one of the aforementioned mechanical devices.
- All water level tapes and meters should be calibrated against one master tape which is traceable to the National Institute of Standards and Technology. This calibration should be recorded in the field logbook.
- Repeated measurements at any one well should be made using the same tape.

3.1 SELECTION OF TEST METHOD

Before beginning any aquifer test, the investigator should have a good conceptual model of the site's hydrogeologic condition. This is essential because of the assumptions made in each

2. Field portable computer and associated equipment are considered as optional. Access to a computer will be required to down-load dataloggers.

analysis method. If the site conditions do not correspond with the assumptions in a given model, the analysis will be invalid. The conceptual understanding of the hydrogeology of the site can be developed from driller's logs and/or borehole geophysical logs of the wells to be tested, or from previous reports on the hydrogeology of the area. Table SOP033-1 is a decision tree which can be used with this conceptual model to determine the appropriate test/analysis method(s) which may be used at a given site.

3.2 PUMPING TESTS

Pumping tests can be divided into two broad categories: (1) those in which the pumping (discharge) rate is kept constant, and (2) those in which the pumping rate varies over time. All water removed from pumping wells must be disposed of appropriately.

3.2.1 Constant Discharge

These methods require that the discharge or injection rate in the pumping well be kept constant. Of these, the Theis method is the most widely referenced and applied, and serves as the basis for the solution of other, more complex boundary condition problems. Both the Cooper & Jacob and the Jacob modifications to the Theis method recognize that if pumping times are long and/or the distances to control wells are small, the Theis solution will yield a straight line plot on semilogarithmic paper, thereby simplifying the Theis equation. The Thiem method, unlike the Theis/Modified Theis methods, assumes that steady-state (equilibrium) conditions can be achieved in a confined aquifer.

The Theis method is detailed in Section 5.1.1 and ASTM D4106, the modified Theis method in Section 5.1.2 and ASTM D4105, and the Thiem method in Section 5.1.3.

The preceding methods assume that the aquifer being tested is confined. If the aquifer is unconfined or semi-confined (leaky), the preceding methods are invalid. DeGlee developed an equation which assumes that the tested aquifer is either overlain or underlain by a continuous, leaky confining layer which has uniform properties, and that leakage from the aquitard is proportional to the hydraulic gradient across the aquitard. Hantush and Jacob derived the same equation. Hantush later observed that a simpler approximation is possible if the ratio of the distance to monitoring well/leakage across the aquitard is <0.05. As in all preceding cases, radial flow is assumed. The Hantush-Jacob method assumes that no storage occurs in the aquitard. The DeGlee equation and Hantush approximation is provided in Section 5.3.2.

Both Neuman and Witherspoon, and Hantush have proposed methods that take into account storage in the aquitard. The Neuman/Witherspoon method is provided in Section 5.3.1.

3.2.1.1 Field Operations

1. Arrange for all nearby extraction wells and automatic pump controls to be inoperative during the test period.

2. Measure and record the distance(s) between observation well(s) and pumping well.

3. Install pressure transducers in the pumping well and each observation well; submerge the transducer in the well to a sufficient depth to provide effective performance. Well bottom sediment plugging of the transducer must be avoided.

4. Perform a two-point calibration of each device as part of the installation, cross-checking data with a calibrated manual tape measure. Note that water levels must be noted and recorded to the nearest 0.01 ft.

5. Start dataloggers at each well several days before the test to record background fluctuations in the groundwater table. It is recommended that one observation well be selected beyond the expected influence of the test to monitor these background water table fluctuations during the actual test.

6. Using either the field barometer of data from a local meteorological station (Section 2.2), record precipitation and barometric pressure before, during and after the test.

7. Calibrate pump, flowmeter, and any other field instruments such as pH meters, etc.

8. Suspend pump at mid-point of pumping well screen and record water level.

   - If the recharge rate of the well is not known, conduct a step-drawdown test (Section 3.2.3) to determine the sustainable yield for the constant discharge test.

   - If the previous step is performed, the aquifer must be allowed to recover prior to performing the constant discharge test. At a minimum, the recovery period between step-test and pump test must be equal to the duration of the step test.

   - Manually check and record the water levels in all test wells before conducting the step test, at the end of the step test, and at 4-hour intervals (minimum) during the recovery period; recording these values in the field logbook.

9. Program the datalogger data acquisition rate as follows:

   - If the only mode of data acquisition is a fixed rate, program the datalogger(s) to record water levels every 5 seconds.

   - If a logarithmic data acquisition rate is possible, use this option.

   - If the data acquisition rate is programmable on the data logger, record data at incrementally lengthening frequencies. The following table is provided as an example, the actual rates at which data are acquired at a given site should be determined based on prior field tests.

Time after Aquifer Test Begins	Frequency of Measurements
0-60 minutes	Every 5-10 seconds
61-65 minutes	Every 15 seconds
65-75 minutes	Every 30 seconds
75-120 minutes	Every 5 minutes
120-180 minutes	Every 10 minutes
180 minutes – end of test	Every 30 minutes

10. Collect a complete round of static water levels, verifying transducer readings with a tape or electric water level meter.

11. Start data logger(s).

12. Start pump at previously selected rate. Monitor flow rate using flowmeter or stopwatch and bucket (rain gauge, graduated cylinder, etc.) half-hourly. Record this flow rate and adjust as necessary. Minimize fluctuations in flow rate, especially during the early stages of the test.

13. Periodically download data from the loggers and plot drawdown as a function of time to assess the status of the test in real time. Under no circumstances should the flow rate be varied during the test.[3] If drawdown is either falling substantially above or below predicted levels, then a decision should be made to continue the test at that pumping rate, terminate the test, allow the aquifer to recover, or restart the test at a different pumping rate.

14. Continue pumping and recording water levels for a total period of 72-96 hours (3-4 days). After the drawdown portion of the test, download the data onto data diskettes using the portable computer.

15. Reprogram the dataloggers to record a reading every 5 seconds or a logarithmic or variable interval if available on the datalogger.

16. Turn off the pump and allow the groundwater to recover to within 90 percent of static conditions. The pump should be equipped with a foot valve to prevent backflow of the column pipe fluid.

17. Periodically download data from the logger and plot recovery as a function of time to assess the status of the test in real time.

3. After a period of at least 12 hours into the test, brief interruptions (less than 5 minutes) in pumping due to mechanical failure are acceptable without re-starting the test. All critical equipment should have onsite backups as a contingency against equipment failures. Inasmuch as refueling an onsite generator every 4-10 hours while it is running is considered an unsafe practice, two generators should be provided at the pumping well site to maintain power to the pump during the test.

18. After recovery to 90 percent of static conditions, remove the dataloggers, pressure transducers, and cables from all the observation wells. Download the data onto data diskettes using the portable computer.

19. Collect a complete round of water levels from all wells in the monitoring network.

3.2.2 Variable Discharge

Variable discharge methods have been presented by numerous researchers. These methods are performed as a series of constant-rate, stepped changes in discharge rate. These changes in discharge rate may be linear or exponential. Type curves are derived for control wells. These methods can be applied in extensive leaky aquifers, but are generally used in confined aquifers. The only requirement is that the response to a unit stress be known. The step-test is incorporated as a preliminary measure to determine the optimal sustainable discharge rate for a given aquifer (Section 3.2.1.1). Otherwise, variable discharge methods are included herein for the sake of completeness. They are not widely used outside the research environment for aquifer characterization. No further details on variable pump rate tests are provided in this SOP.

Install a variable speed submersible pump and a pressure transducer into the pumping well.

Install pressure transducers into the nearby (closest) observation wells to provide preliminary indications of expected drawdown during the constant-discharge test.

Allow water level(s) to stabilize to original water level after installing the pump and transducer(s).

Program a datalogger to collect readings at 5- to 10-second intervals. If logarithmic programming is available, this collection period may be expanded to 1-minute increments by the completion of each step, where upon 5- to 10-second intervals will again be required to coincide with the start of the next step.

Measure static water levels from all wells expected to be influenced by the test, and calibrate pressure transducers. Record this information in the field logbook and field data sheets.

Select the pumping rates for the step-test. Four 100-minute steps should be run at steadily increasing flow rates. The flow rates should be selected, based on a preliminary estimate of a sustainable rate (ESR) as follows:

Step	Duration (minutes)	Pumping Rate (%)
1	100	25
2	100	50
3	100	100
4	100	125

Program the dataloggers, calibrate the pump to the initial flow rate, and initiate the test at 25 percent ESR. At the completion of the first step, increase the pumping rate to 50 percent ESR as instantaneously as possible. The pump should not be shut off between steps. At the completion of the second step, increase the flow rate to 100 percent ESR as instantaneously as possible. At the completion of the third step, increase the flow rate to 125 percent ESR as instantaneously as possible. At the completion of the fourth step, shut off the pump and record the recovery of water levels to at least 90 percent of static conditions.

During the test, plot drawdown in the pumping well on both arithmetic and semi-logarithmic graph paper to assess the performance of the test in real time. Make any adjustments to the test as appropriate, i.e., the addition of a fifth step at a higher rate if the aquifer does not appear to be adequately stressed, or termination of the test if the well is drawn dry.

At the conclusion of the test, analyze the data and select a pumping rate for the constant-discharge test. This rate should be sustainable for the anticipated duration of the test, and place the maximum stress on the aquifer.

Calibrate the variable speed pump to the selected rate so that at the start of the constant discharge test early fluctuations in flow rates will be minimized.

Allow the aquifer to fully recover for a period equal to or greater than the duration of the step-test prior to initiating the constant-discharge test.

3.3 SLUG TESTS

Slug tests involve the use of a single well, and evaluating its response to an instantaneous raising and/or lowering of the water level within the casing. If the well is poorly designed or poorly developed, the test may end up evaluating the performance of the well screen and/or filter pack rather than the aquifer.

Slug tests are usually of short duration, usually less than 5 minutes. The first 30 seconds are the most important in respect to data collected. Piezometers and digital data loggers are, therefore, a must.

3.4 DATA REDUCTION

If the data were recorded by the datalogger as feet of water above the pressure transducer, reduce these data to potentiometric head (in feet), relative to the initial water level as measured from the top of the casing. Record this with the respective changes in time. For each piezometer or well, tabulate the pre- and post-test water levels, dates, clock times, and times since pumping started or stopped.

Tabulate measurements of the rate of discharge at the control well, date, clock time, time since pumping started, and method of measurement.

Prepare a written description of each well, describing the measuring point, giving its elevation and the method of obtaining the elevation, and the distance of the measuring point above the mean land surface.

Once the data are collected and reduced, a variety of methods may be used to calculate aquifer parameters from pumping test data. Refer to Section 5 for analytical methods applied to test data.

Data can also be reduced electronically when downloaded from the transducers into software such as AQTESOLV®; this is software designed to calculate hydraulic conductivity, storativity and other aquifer properties from data sets collected during slug and aquifer (pumping) tests.

Text files, which are generated by commonly used pressure transducers, can be imported into the software and data can also be manually entered or pasted from a spreadsheet. After importing, the raw data can be manipulated using mathematical functions. For example, hydraulic head data can be converted to drawdown data. The program will also produce visual and automatic curve matching methods for confined, unconfined and leaky aquifers. Visual curve matching is analogous to traditional methods of aquifer test analysis with graph paper and type curves. The software is also capable of producing error logs which enable the user to quickly identify any deficiencies or inconsistencies detected in the data set.

4. FIELD DATA RECORDS

4.1 LOGBOOK

Only one site or installation per logbook, and only one slug test per data table (see below). The first page must include the well number, location, date of test, persons conducting the test, and reference plane for drawdown measurements. Next page(s) must be in table format with the columns designating time/date, water volume withdrawn/added or displaced by inert cylinder, water levels, etc.

Test data must be entered in a table as data are acquired. Data must include sufficient information to indicate that the water level was stable before the test, during equilibrium, and after the test(s).

5. INTERPRETATION OF DATA

5.1 CONFINED AQUIFER METHODS

5.1.1 Theis Method

The Theis test method involves pumping a well (pumped well) at a constant rate (Q) and measuring drawdown (s) in an adjacent observation well. Theis assumed that groundwater flow in an aquifer is analogous to heat flow in a solid and derived the following equation:

$$s=\frac{Q}{4\pi T}\int_{\frac{r^2 S}{4T\,t}}^{\infty}\left(\frac{e^{-u}}{u}\right)du \qquad \textbf{Equation 1}$$

where

- s = Drawdown.
- r = Radial distance to observation well.
- Q = Pumping (discharge) rate.
- T = Transmissivity (K × aquifer thickness).
- K = Conductivity.
- S = Storativity.
- t = Time (since pumping began).

and

$$u=\frac{r^2 S}{4T\,t} \qquad \textbf{Equation 2}$$

If the integral is expressed as the well function W(u), then the equation can be written as:

$$s=\frac{Q}{4\pi T}W(u) \qquad \textbf{Equation 3}$$

which can be also written as:

$$T=\frac{Q}{4\pi s}W(u) \qquad \textbf{Equation 4}$$

or

$$S=\frac{4Tt}{r^2}u \qquad \textbf{Equation 5}$$

5.1.1.1 Assumptions

To permit an analytical solution for non-steady, radial flow into the well, the Theis method makes the following assumptions. Most of these assumptions are incorporated in the other analysis methods detailed herein. Only exceptions or additions to these assumptions will be noted in each method.

- The aquifer has seemingly infinite areal extent compared to the well, whose diameter is assumed infinitesimally small.
- The aquifer is homogeneous, isotropic, of uniform thickness, and horizontal.
- The head is uniform and constant prior to the test.
- Darcy's Law is valid.
- The well is pumped at a constant rate.
- Water is discharged from storage instantaneously.
- The well screen fully penetrates the aquifer.
- Flow within the aquifer is radial to the well and strictly horizontal.
- Drawdown data are taken from an adjacent observation well.

One additional assumption is made in this SOP, which was not made by Theis: The pumping well has been previously sampled and analysis of the groundwater at that site is not grossly contaminated (e.g., no non-aqueous phase liquids).

5.1.1.2 Procedure (see also ASTM D4106-91 and D4050-91)

Field Operations – Constant Discharge Test (Refer to Section 3.2.1)

Data Plots

1. Prepare a type curve of W(u) over 1/u on log-log paper. Figure SOP033-1 is an example of a type curve. Tables of data used to generate this curve may be found in ASTM D4106-91, ASTM D5270-92, or in most hydrology texts such as Fetter or Dominico[4]. It is recommended that this plot be copied onto tracing paper, drafting film, or an overhead viewer film copy be made to facilitate later steps. NOTE: W(u) over u can be plotted if preferred, but will require additional computational steps if used.

2. Plot drawdown over time for each observation well on log-log paper which has the same scale as the type curve (above). Note that for a single observation well, drawdown can be plotted as a function of time (t). However, for multiple observation wells, drawdown can be plotted as a function of t/r2, where r = radial distance from the pumping well to the observation well in which the measurements were made. This is done to normalize the data and allow comparison between wells.

4. See Section 6 for complete citations of these references.

3. Superimpose the type curve and the plot of observation well data. **Keeping both the X and Y axis of each plot parallel**, position the two curves to obtain the best match when overlain. NOTE: If only paper copies of both plots are available, a light table or brightly lit window will be required for this step.

4. Select a match point on the overlapping portion of the two graph papers such that the values for that point simplify the calculations (e.g., even log cycles of [W(u), 1/u] — [1,1]; [1,10] etc.).

5. Read coordinates for W(u), 1/u, s, and t.

6. Substitute the match point values for the appropriate variable in Equations 3, 4, and 5.

7. Repeat for each observation well.

5.1.2 Modified Theis (Cooper & Jacob; Jacob) Method (see also ASTM D4105-91)

5.1.2.1 General

From Equation 1, we have:

$$\int_u^\infty \left(\frac{e^{u}}{u}\right)du = W(u) = -0.577216 - \log_e u + u - \frac{u^2}{2!2} + \frac{u^3}{3!3} - \frac{u^4}{4!4} + \ldots$$

Equation 6.

Jacob noted that as values of u become small, the value of the series to the right of logeu becomes insignificant. That is the series becomes equal to or less than 0.01. The value of u decreases as the value of t (time) increases, and as the value of r (radial distance to observation well) decreases. Therefore, for long pumping times and/or observation wells reasonably close to the pumping well, the Theis equation can be stated as:

$$s = \frac{Q}{4\pi T}\left[-0.577216 - \ln\left(r^2 \frac{S}{4Tt}\right)\right]$$

Equation 7.

Lohman was then able to show the following relationships:

$$T = \frac{2.3Q}{4\pi \Delta s/\Delta \log_{10} t}$$

Equation 8

and

$$T = \frac{2.3Q}{4\pi \Delta s/\Delta \log_{10} r}$$

Equation 9

where

Δs/Δlog10t = The drawdown (measured or projected) over one log cycle of time.
Δs/Δlog10r = The drawdown (measured or projected over one log cycle of radial distance from the control well.

5.1.2.2 Procedure

Field Operations (see Field Operations under Section 3.2.1.1)

Data Plots

1. Plot drawdown over time (log scale) on semilog paper.

2. Draw a best fit straight line through the later portion of the data and project it back to s = 0.

3. Read t0 as the time corresponding to the s = 0 point.

4. Solve for T using:

$$T = \frac{2.3Q}{4\pi\Delta s}$$

Equation 10

5. Solve for S using:

$$S = \frac{2.25Tt_0}{r^2}$$

Equation 11

where

t0 = the intercept of the line when extended to the zero drawdown axis.

6. Solve for K (K = T/aquifer thickness). Aquifer thickness = screened interval (see assumptions in Section 5.1.1.1).

7. Repeat for each monitoring well.

5.1.3 Thiem (Steady State Flow) Method

5.1.3.1 Assumptions

All of the Theis assumptions hold except that equilibrium has been reached between discharge and drawdown. Note that this condition is theoretically impossible in a confined aquifer where all discharge is derived from storage.

5.1.3.2 Equations

When these assumptions are met, the following equation expresses groundwater flow in the confined aquifer:

$$Q = \frac{2\pi T(s_1 - s_2)}{\ln(\frac{r_2}{r_1})}$$

Equation 12

where

Q = Well discharge.
T = Aquifer transmissivity.
r1 and r2 are respective distances of OW-1 and OW-2 from the pumping well.
s1 and s2 are respective steady-state drawdowns in the observation wells.

Note that the Thiem equation is designed to solve for transmissivity only, and cannot be used to solve for storativity.

5.1.3.3 Procedure

Field Operations

1. Follow Steps 1 through 9 in Section 3.2.1.

2. Continue pumping until steady-state conditions are reached. This equilibrium is defined as the time when variations of drawdown with respect to time are negligible. Note that this may require considerably more time than with either the Theis or Modified Theis methods described above.

Data Plots Method 1

1. Substitute the steady-state drawdown of the two observation wells into Equation 12 along with the values of r and Q. Solve for T.

2. Repeat with all possible combinations of observation wells to obtain the mean transmissivity of the aquifer.

Data Plots Method 2

1. Plot the observed steady-state drawdown of each observation well over distance (log scale) to the pumping well.

2. Construct a best-fit straight line through the plotted points.

3. Determine the maximum drawdown per log cycle.

4. Substitute this value of (s1 - s2) in Equation 12 along with Q and solve. Note that the term ln(r2-r1) is taken to ln(10) equal to 2.30.

5.2 BOUNDED, NON-LEAKY, CONFINED AQUIFER

The test methods described in this section are essentially duplicates of the Theis and Modified Theis methods which are detailed above. The principal differences are that, by definition, a bounded aquifer is limited in its areal extent by a fully-penetrating linear boundary, which is either a constant head (e.g., stream or lake) or a no-flow boundary (e.g., impermeable, or significantly less permeable geologic formation). These conditions are illustrated on Figure 2.

As stated, the equations used to evaluate data derived from bounded wells are modifications to the basic Theis equations. Drawdown(s) at any point in the aquifer is defined as the sum of the drawdown due to the real ($_r$) and image ($_i$) wells such that:

$$s_0 = s_r \pm s_i$$ **Equation 13**

so that Equation 1 can be rewritten as:

$$s = \frac{Q}{4\pi T}[W(u_r) \pm W(u_i)] = \frac{Q}{4\pi T}\sum W(u)$$ **Equation 14**

where

$$u_r = \frac{r_r^2 S}{4Tt}$$ **Equation 15**

and

$$u_i = \frac{r_i^2 S}{4Tt}$$ **Equation 16**

so that:

$$u_i = \left(\frac{r_i}{r_r}\right)^2 u_r$$ **Equation 17**

or

$$u_i = k_i^2 u_r$$ **Equation 18**

where

$$K_l = \frac{r_i}{r_r}$$ **Equation 19.**

NOTE: K_1 is a constant of proportionality and should not be confused with the hydraulic conductivity.

5.2.1 Assumptions

All assumptions listed under the Theis method apply with these exceptions:

- The non-leaky aquifer is of infinite areal extent except where limited by linear boundaries.
- The boundaries are vertical planes of infinite length, which fully penetrate the aquifer.
- The hydraulic boundaries are perfect. Impermeable boundaries yield no water to the aquifer; recharge boundaries are in perfect hydraulic connection with the aquifer.

5.2.2 Procedure (see also ASTM D5270-92)

Field Operations (see Section 3.2.1.1)

Data Plots

1. Generate a family of type curves for the solution of the modified Theis formula (Kl). This family of curves should include curves for both discharging and recharging image wells. Plot the coordinates of ∑W(u) on the vertical axis and 1/u (Figure 3). It is recommended that this plot be copied onto tracing paper, drafting film, or an overhead viewer film copy be made to facilitate later steps.

2. Plot drawdown (s) over t/r2 for each observation well on log-log paper which has the same scale as the type curve (above). NOTE: **t=time, r=radial distance from pumping well.**

3. Superimpose the type curves and the plot of observation well data. **Keeping both the X and Y axis of each plot parallel**, position the two curves to obtain the best match when overlain. NOTE: If only paper copies of both plots are available, a light table or brightly lit window will be required for this step.

4. Select a match point on the overlapping portion of the two graph papers such that the values for that point simplify the calculations (e.g., even log cycles of [∑W(u), 1/up] — [1,1]; [1,10] etc.).

5. Read coordinates for ∑W(u), 1/up, s, and t/r2.

6. Substitute the match point values for the appropriate variable in the equations below:

Transmissivity = $$T=\frac{Q}{4\pi s}\sum W(u)$$

Equation 20

Storativity = $$S=4T\left(\frac{t}{r^2}\right)u$$

Equation 21

7. For each OW, determine the distance from the image well (r_i) using the following:

$$r_i=K_f r_r$$

Equation 22

8. Repeat for each observation well.

5.2.3 Modified Theis Non-Equilibrium Method

As in the case of a non-bounded aquifer, the hydraulic parameters can also be determined using a Modified Theis equation and a straight line (semi-log) plot of s and log10t.

5.2.3.1 Procedure

1. Refer to Section 5.1.2 (above) and ASTM D4105-91 for details on plotting the data and the equations to be used in calculating transmissivity and storativity using this method. Note that the data will define two rather than one straight line portions. This is due to the image well effect of the boundary conditions.

2. Select a convenient value of s within the initial straight-line part of the plot. Drawdown represented by this portion of the curve has not been affected by the boundary. Therefore, s = sr and the corresponding value of tr corresponds to sr.

3. Graphically extend the initial straight-line part of the curve to the right. The departure of the measured drawdown from the extended line represents the drawdown due to the presence of the boundary. This effect is also referred to as the image well drawdown, si.

4. Select a point on the second straight-line such that si = sr. Note the value of time ti which corresponds to si.

5. Since tr and ti are selected such that si = sr, then ur = ui and (Equation 23)

   $$\frac{r_r^2 S}{4Tt_r} = \frac{r_i^2 S}{4Tt_i}$$

   so that:

   $$K_i = \frac{r_i}{r_r} = \sqrt{\frac{t_i}{t_r}} \qquad \text{(Equation 24)}$$

6. Determine the distance to the image well using Equation 22.

7. Repeat this calculation for each observation well.

Determine the location of the boundary as follows:

- Accurately plot the locations of the control and observation wells on a map.

- With a compass, using each observation well as the center point, draft a circle which has a radius equal to the distance from that well to the boundary.

- The image well is located at the intersection of these circles. If the circles do not intersect exactly, the probable well location is at the centroid of the intersections, or the polygonal area bounded by the circles in the case of no overlap.

- Draw a straight line from the pumping well to the image well. The boundary is defined as the perpendicular bisector to this line at the image well.

5.2.4 Limitations

The following caveats apply to either of the above two methods:

- In cases where this test method is employed to locate an unknown boundary, a minimum of three observation wells is required to accurately locate the image well which is the boundary. Two observation wells will yield two possible locations for the image well. One observation well will indicate the presence of a boundary, and the distance (radius) from the observation well, but the image well will be located somewhere on that surface.

- The effects of a constant head (recharging) boundary are indistinguishable from those of a leaky aquifer. It is, therefore, imperative that care be taken in developing the conceptual model of the geohydrologic system being studied prior to testing.

5.3 SEMI-CONFINED (LEAKY) AQUIFER

In some instances, the confining beds either above or below the aquifer will not be completely impermeable. In these cases, the aquifer is said to be "leaky." This condition can be readily determined from the Theis s over t plot on log-log paper. In the initial phase of pumping, the plot will look like the Theis "type" curve. As pumping continues and the aquifer is depressurized (piezometric head decreases), a gradient within the overlying and/or underlying aquitard(s) is induced. Instead of the expected type curve, the plot will be somewhat flattened, and values for s may actually decrease over time if the vertical component of groundwater flow through the aquitard(s) is sufficiently high. The log-log plot will yield a considerably flattened curve. This is one of the reasons it is recommended that these log-log plots be done in the field, so that such conditions can be detected early, and steps be taken to minimize any adverse environmental impact of aquifer cross contamination.

5.3.1 Neuman and Witherspoon Method

The Neuman and Whitherspoon approach to solving the problem of evaluating a leaky aquifer is two-fold. First, they assumed that if the distance between observation well and pumping well is minimized, the area of aquitard subjected to stress and possible leakage is minimized, and the Theis method could be employed. Next, they assumed that if only early time drawdown data were used, the effects of leakage could be further reduced. This is accomplished by closely monitoring the response curve(s) for transducers both in the aquifer and in the aquitard(s) themselves. When the s over t curve begins to flatten, indicating leakage, this is defined as the end of valid aquifer data. Data acquired beyond that point contains components of horizontal (aquifer) flow, and vertical (aquitard) flow. In order to accurately calculate the aquitard parameters, an undisturbed sample of the aquitard must be taken (ASTM D1587-83). The laboratory tests will provide values for storage of the aquitard(s). Conductivity within the aquitard(s) is provided from the s over t plots for transducers located within the aquitard.

5.3.1.1 Assumptions

The same assumptions as in the Theis method hold with the following differences:

- The aquifer is leaky.
- The aquifer and aquitard both have a seemingly infinite areal extent.
- Flow in the aquitard is vertical.
- Drawdown is negligible in both aquifer and aquitard.
- The aquitard has storage.
- The overlying and/or underlying aquifer(s) is capable of releasing water to the pumped aquifer through a decline in head.

5.3.1.2 Procedure

Field Operations

1. See field operations in Section 3.2.1.1.
2. In addition, set piezometers within the aquitard at 0.25 and 0.50 aquitard thickness. These should be set at essentially the same location as the observation well, either in the observation well or in a separate borehole adjacent to the observation well, and the same radial distance from the pumping well.

Data Plots

1. Prepare log-log plots of s over t for the observation well and transducers placed in the aquitard.
2. Use the valid early-time data and the Theis method to calculate the pumped aquifer parameters.
3. Calculate several s'/s ratios for the early time period used in b above.
4. Calculate the parameter tD — a "dimensionless" time parameter — using the following equation:

$$t_D = \frac{Kt}{Sr^2}$$

Equation 25

where

t = Time.
r = Radial distance to observation well (and transducers).
K = Pumped aquifer hydraulic conductivity.
S = Pumped aquifer storativity.

5. Using the value tD calculated in d (above), and s'/s, determine a value for t'D using Figure 4.

5.3.2 DeGlee Method and Hantush Approximation

DeGlee developed the following equation for steady-state drawdown within an aquifer with leakage from an aquitard proportional to the hydraulic gradient across the aquitard:

$$s = \frac{Q}{2\pi T}(K_0)\frac{r}{L} \quad \text{Equation 26}$$

where

T = Transmissivity.
s = Steady-state drawdown in observation well at distance r from pumping well.
Q = Discharge rate of pumping well.
L = Tc = leakage factor.
c = D'/K = hydraulic resistance of the aquitard.
D' = Saturated thickness of the aquitard.
K' = Hydraulic conductivity of the aquitard for vertical flow.
K0(x) = Modified bessel function of the second kind and of zero order (Hankel function).

Hantush observed that if r/L is small (0.05), Equation 14 can be estimated by:

$$s = 2.30\frac{Q}{2\pi T}(\log 1.12\frac{L}{r}) \quad \text{Equation 27}$$

5.3.2.1 Assumptions

See Section 5.3.1.1.

- Flow to the pumping well is in steady state.
- L is greater than 3D, where D is the saturated thickness of the aquifer.

5.3.2.2 Procedure

Field Operations

Field methods are identical to the Thiem method in Section 5.13.

Data Plots

Plot s over r (log scale) on semi-log paper where r/L is small, the points fall in a straight line plot. Where r/L is large, the curve approaches the zero-drawdown axis asymptotically.

5.3.3 Other Methods for Calculating Leaky Aquifer Parameters

The Neuman and Witherspoon Unsteady-state flow method, the Hantush Curve-Fitting Method, the Hantush Inflection Point Method, and the Walton Method. As before, these are mentioned for the sake of completeness, but not detailed herein.

5.4 UNCONFINED AQUIFERS

Flow to a pumping well in an unconfined (phreatic or water table) aquifer occurs in three phases. In the first phase, pumping has just begun, and the aquifer acts like a confined aquifer. Water is derived from storage (expansion of the water, compression of the aquifer). The time over drawdown plot for this phase closely mimics the Theis type curve. During the second phase, delayed yield occurs. This phenomenon results as water remaining in the pores is drained by gravity (specific yield), replenishing the portion of the aquifer supplying water to the well during the first phase, and results in a reduction in rate of drawdown over the first phase, and a flattening of the time-drawdown plot. The third phase brings equilibration in the rate of drawdown and the time-drawdown plot again looks like the Theis curve.

The duration of the first two phases is a function of the ratio of storage (S) to specific yield (Sy). If the ratio is in the range of 10-1 to 10-2, S is relatively large and the first phase drawdown should be significant. This condition is typical of saturated fine-grained sediments such as silts, clays, and fine-grained sands. If the ratio S/Sy is in the range of 10-4 to 10-6, Sy is relatively large, the second phase phenomenon is expected to be dominant, and coarser-grained sediments (sands and gravels) are indicated.

In addition to S/Sy, the distance between pumping well and observation well also affects the time-drawdown plot. As the distance to the observation well increases, the effects of S decrease.

5.4.1 Neuman Method

Flow to a pumping well in an unconfined (phreatic, or water table) aquifer occurs in three stages. During the first stage, the phreatic aquifer behaves like a confined aquifer, instantaneously releasing water from storage (expansion of the water, compression of the aquifer). This is illustrated in Figure 5, where the early portion of the family of drawdown curves closely matches the Theis curve (1/uA). The second phase is termed a period of "delayed yield" or "delayed response," in which the rate of drawdown is lower than that predicted by the Theis curve. During this phase, specific yield, or gravity drainage of water remaining in the pore spaces in the vicinity of the pumping well replenishes the water being removed. During the third phase, the rates of yield and drawdown equilibrate, and the time-drawdown plots again converge on the Theis solution (1/uB).

5.4.1.1 Assumptions

- The same assumptions as listed in Section 5.1.1.1.

- At least one observation well located at $r/b \leq 1$, where r = distance between pumping well and observation well, and b = aquifer thickness.

Drawdown in the observation well $s \leq 0.25$ b.

5.4.1.2 Procedure

Field Operations

See Section 3.2.1.
Data Plots

1. Prepare A and B curves (Figure 5); tables of these values can be found in many hydrology texts such as Fetter

2. Plot s over t on log-log paper at the same scale as the Type A and B curves

3. Superimpose the late-time drawdown data over the B curves. Note the value for the curve which best matches the field data.

4. Select a match point which has a value of 1 for as many of the variables as possible.

5. At the selected match point, read values for s, t, W(uB,β) and 1/uB

6. Repeat steps a-e, superimposing the early time data over the A curve which has the same β value as the B curve.

7. Read values for s, t, W(uA,β) and 1/uA

8. Substitute these values in the following equations:

$$T_B = \frac{Q}{4\pi s}(W(u_B',\beta))$$

Equation 28. Transmissivity B curve.

$$T_A = \frac{Q}{4\pi s}(W(u_A', \beta))$$

Equation 29. Transmissivity A curve.

$$S_y = \frac{4T_B t u_B}{r^2}$$

Equation 30. Specific Yield.

NOTE: Transmissivities should be within ±10 percent of each other. If they are, their average should be used in the remaining equations, otherwise use the T value from the B curve.

5.5 SLUG TESTS

5.5.1 Preliminary to Operation (All Slug Tests)

Prior to conducting any tests, water level meters, transducers, dataloggers, and other materials should be examined for cleanliness and checked for defects.

Batteries should be checked in the calculator(s), water level meter(s), and datalogger(s).

Decontaminate all intrusive equipment prior to and after use at each location.

Lay plastic sheeting on the ground around the well casing.

Record the well number and other project and site information in the field logbook.

Check the well headspace for the presence of volatile organic compounds using applicable instruments. Record the results in the field logbook.

Measure and record the initial water level in the well and total depth of the well.

NOTE: If the static water level and water levels caused during testing are above the top of the screened, or the well consists of an open hole with no casing, then both rising-head and falling-head tests should be conducted.

If the static water level is at or below the top of the screened or open-hole interval, a rising-head test only should be conducted (i.e., falling-head slug tests are invalid for this situation).

5.5.2 Option 1 – Inert Object Insertion

This procedure describes the use of a solid slug to change the water level in a well.

Select an appropriate transducer for the range of water level change anticipated in the slug test.

Submerge the transducer in the well to a sufficient depth to provide effective performance. The range of the transducer must be considered in the determination of the submersion depth. Well bottom sediment plugging of the transducer must be avoided as well as transducer interference by the inert object.

Monitor water level until it returns to original level as measured in Section 5.5.2 before initiating the test.

Tie off the line to a decontaminated, inert cylinder (slug) prior to lowering it into the well. All intrusive equipment must be decontaminated.

"Instantaneously," but smoothly, lower the cylinder into the well, displacing the water and thereby raising the water level.

Measure and record water levels in the well initially. Record the water level response during cylinder insertion and every 5-10 seconds with the cylinder in place. Record the falling water level and time of each measurement in the field logbook and/or Field Permeability Test Data Sheet.

NOTE: If transducer and datalogger are employed, care must be taken to create backup copies and/or hardcopies of these data as soon as practicable.

Record data until water level has stabilized, or approximately 90 percent of the change in the water level has dissipated. The time for this to occur may range from less than 1 minute to more than a day. Usually, it is not necessary to continue measurements for more than a few hours because longer periods indicate extremely low hydraulic conductivity. Choose the time interval between measurements according to how rapidly the water level approaches the static level. From 10 to 30 measurements should be obtained at approximately equal time intervals during the recovery.

"Instantaneously," but smoothly, remove the cylinder from the well.

Conduct a rising head slug test by measuring the response of the water level to the removal of the cylinder. Record water levels and time until the water level equilibrates to 90 percent of the initial level, and record data as in Section 5.5.2.

Calculate the aquifer hydraulic conductivity using appropriate equations.

Decontaminate the slug and the tape or meter.

5.5.3 Option 2 – Adding or Removing Water

This procedure describes the use of a pump to change water level in a well and a datalogger and pressure transducer to measure the water level. The technique is intended for use in wells installed in highly permeable materials where the use of a slug may not induce a measurable change in the water level. However, this technique can also be used in wells installed in low permeability materials. The methods described for the transducer/datalogger are also appropriate when using a solid slug or bailer for inducing a change in the water level in a well.

Select an appropriate transducer for the range of water level change anticipated in the slug test.

Submerge the transducer in the well to a sufficient depth to provide effective performance—usually this is to a depth at which its pressure rating is not exceeded but no less than 5 ft of water is above the transducer. The range of the transducer must be considered in selection of the submersion depth.

Check the transducer calibration at two different depths in the well. The transducer should be at least 1 ft above the bottom of the well to prevent bottom sediment from fouling the transducer and preventing accurate readings.

Turn on the datalogger to view the water level value (either in depth of submergence or depth to water).

IF REMOVING WATER: Insert the pump piping with check valve (if using a centrifugal pump) or submersible pump with check valve into the well at least 4 t below the water table but above the transducer. Attach pump discharge to treatment system, portable tanks, or drums to containerize the effluent if it is known or suspected to be contaminated.

— OR —

IF ADDING WATER: Insert piping from water source to a depth of about 1 ft below the surface of the water table (this will prevent undue aeration of the water column and possible anomalous readings).

Monitor water level until it returns to original level as measured in Section 3.1.2 before initiating the water addition/extraction test.

View water level value on datalogger. Values (either depth of submergence or depth to water) should be stable and approximately the same range as in Step C; if not, wait until the water level equilibrates to the initial value.

Begin logging and record the time.

Turn pump on until 4-5 ft of drawdown occurs or the well (at the depth of the poly pipe or pump) goes dry.

— OR —

Turn on water at supply tank until the water level in the well rises a minimum of 5 ft.

Shut off pump or water supply at the tank. Remove piping or pump to a position above the initial water level (water removal) or remove from the well (water addition or removal).

Record water levels and water volumes removed/added during the entire test.

Record water levels until approximately 90 percent of the change in the water level has dissipated. The time for this to occur may range from less than 1 minute to more than a day. Usually, it is not necessary to continue measurements for more than a few hours, because longer periods indicate extremely low hydraulic conductivity.

Periodically collect water levels manually using an electronic water level meter of tape to verify the datalogger values.

End logging and record the time. Remove the poly pipe and/or pump and pressure transducer and transfer data in datalogger to a computer disk. Make a backup copy of the file and record the file information in the field logbook.

Decontaminate intrusive equipment.

Calculate the aquifer hydraulic conductivity using appropriate equations.

5.5.4 Data Plots

Record the water level in the well immediately after the inert object emplacement/withdrawal (Option 1) or at the equilibrium of the water table (Option 2). This is the initial water level reading.

Following the initial water level reading, the water level in the well is continuously recorded along with the time of the level measurement.

The ratio of the initial water level to the change in head is plotted with respect to time.

The ratio is plotted on the arithmetic scale and time is plotted along the logarithmic scale.

The relationships of the initial water level to changes in the water level are a function of parameters shown on Figure 6 and the formation transmissivity. The values of the function relationship are plotted for a series of transmissivities and are depicted in Figure 5.

The resulting field data plot (curve) is compared to a series of type curves (Figure 5). The field-data curve is placed over the type curves with the arithmetic axis coincident. The field data curve is matched to the type curve that has the same curvature.

The formation transmissivity is determined.

The value of storativity is calculated.

6. REPORTS

After performing hydrologic tests, the contractor will generate a report which must contain a minimum of the following elements:

- A field data report including a site description, plots of water level and discharge with time, and a precursory analysis of data.

- The introduction should include the purpose of the test, dates and times water-level measurements were begun, dates and times discharge or injection was begun and ended, and the average rate of discharge or injection.

- Well logs (including construction diagrams) of all control wells, observation wells, and piezometers.

- Site map showing all well locations, distances between wells, and locations of all geologic boundaries or surface waterbodies which might affect the test.

- The locations of wells and boundaries which may affect the test generally need to be accurate within a radial distance of ±0.5 percent. For large-scale studies, it may be sufficient to locate wells from maps or aerial surveys. Small-scale studies require that well locations be surveyed. Additionally, other features such as faults, streams, and canals should be located. Well deviation surveys, which determine true horizontal distance between well screens, may be necessary if test wells are deep relative to their spacing.

7. MAINTENANCE

The transducers must be kept clean, operable, and thoroughly tested before emplacement in the well. A plugged or malfunctioning piezometer will give erroneous responses or fail to give any response.

8. PRECAUTIONS

In the case of slug tests, care should be exercised to maximize the efficiency of the well. If there is a great disparity between the conductivity of the aquifer and that of the well screen/filter pack, one may find that the slug test has accurately measured the conductivity of the well screen/filter pack rather than the aquifer.

Transducers should be double checked to ensure that they are calibrated in the correct water level range. Water level and well depth should be checked with an electronic water level meter or steel tape before and after placing the transducers.

Be sure that the wells used are well developed.

If the water removed is contaminated and cannot be discharged at the surface, a tank of sufficient size to hold the effluent of the pumping test must be available.

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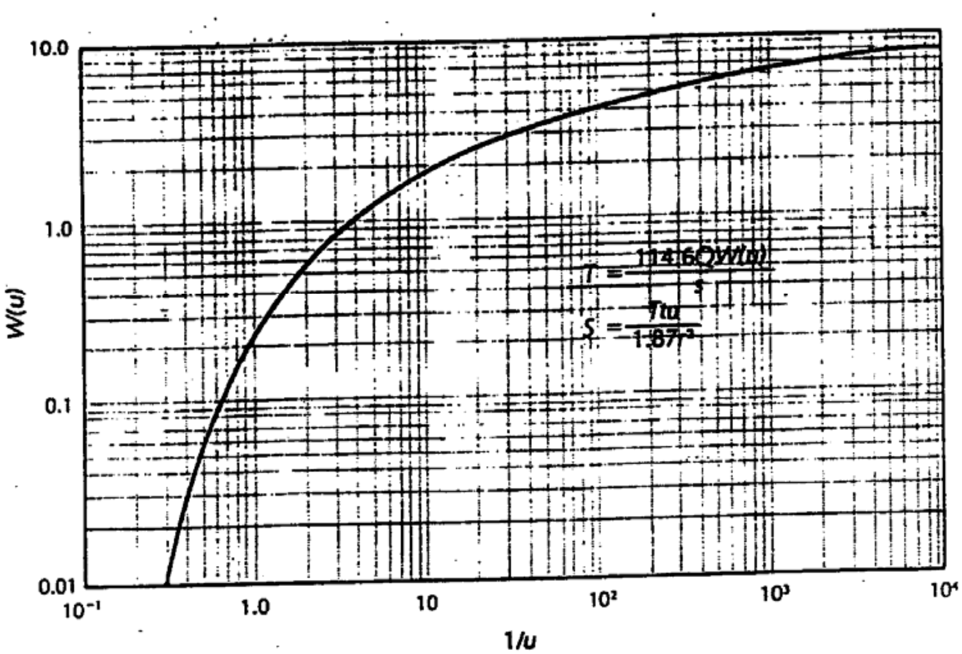

Figure SOP033-1. Theis type curve (after Fetter).

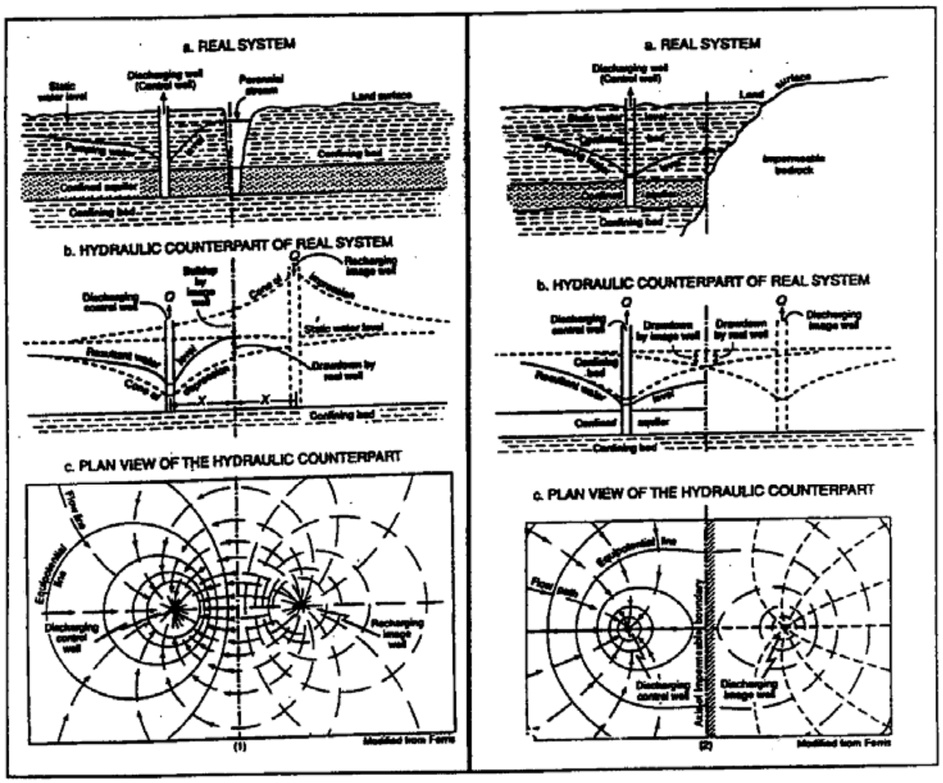

Figure SOP033-2. Illustration of boundary conditions
(after ASTM D-5270-92).

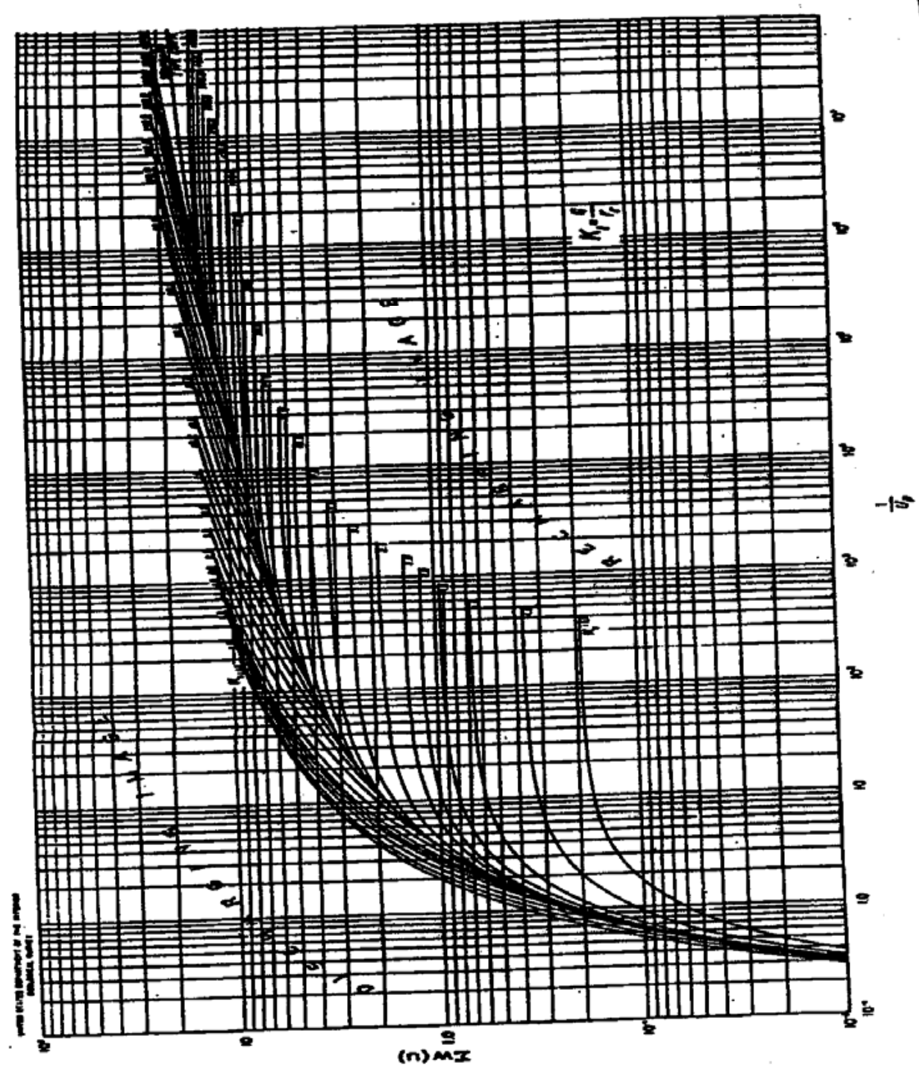

Figure SOP033-3. Family of type curves for the solution of the Modified Theis formula (after ASTM D-5270-92).

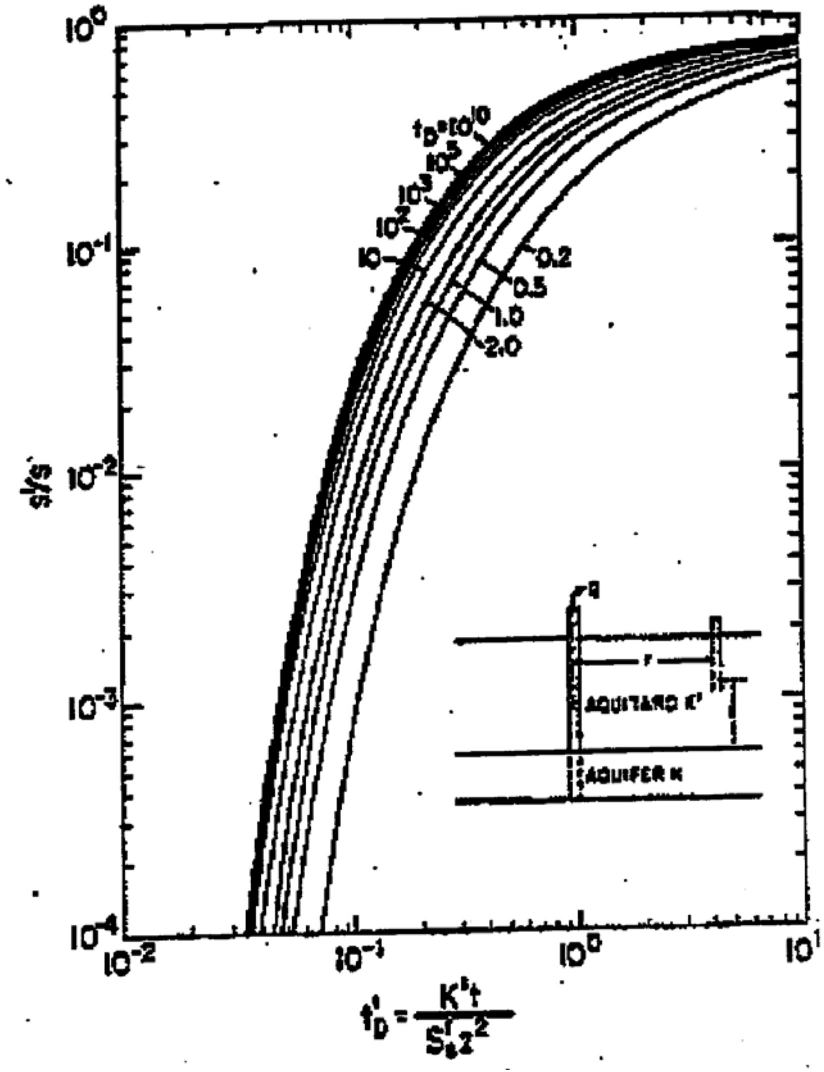

Figure SOP033-4. Variation of s'/s with t'_d for a Semi-Infinite Aquitard (after Reynolds).

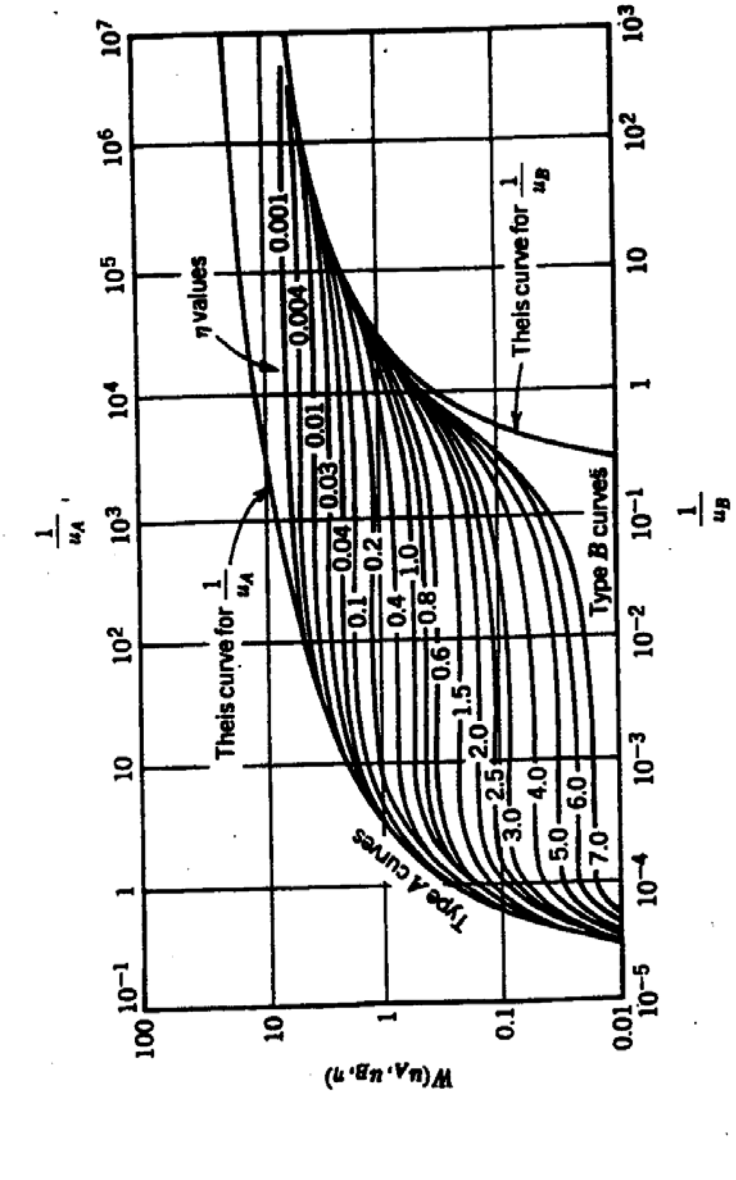

Figure SOP033-5. A and B type curves (after Dominico).

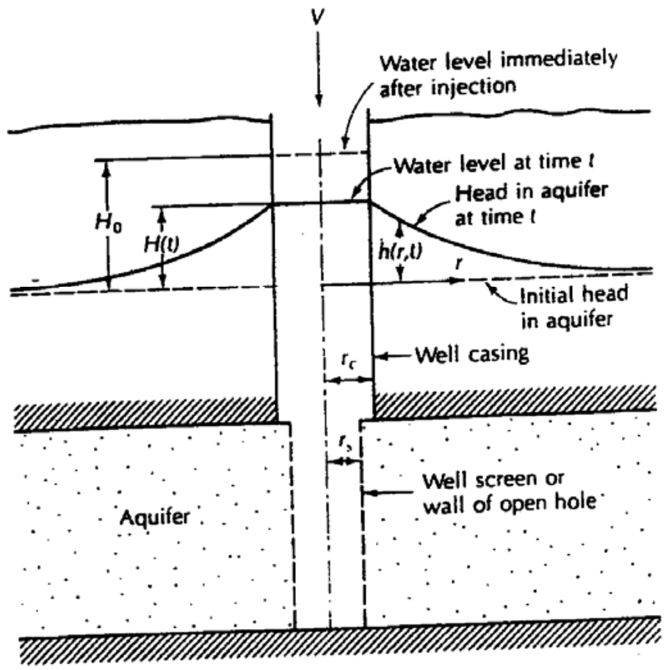

Figure SOP033-6. Well parameters – slug tests (after Fetter).

Fractured Aquifer	= Yes >	Fractured Aquifer Gringarten & Ramey Barenblatt *et al.* Boulton & Stretsova Moench
No ↓		
Single Aquifer	= No >	Multiple Aquifers Bennett & Patten Hantush Neuman & Witherspoon Javendel & Witherspoon
Yes ↓		
Isotropic Aquifer	= No >	Radial-Vertical Anisotropy Hantush Weeks Horizontal Anisotropy Papadopulous
Yes ↓		
Lateral Boundary	= Yes >	Bounded Aquifer Ferris *et al.* Stallman
Yes ↓		
Confined Aquifer	= No >	Unconfined Aquifer: Constant Discharge Boulton Neuman Slug Test Bouwer & Rice Bouwer
Yes ↓		
Leaky Aquifer	= No >	Confined Aquifer: Constant Discharge Theis Cooper & Jacob Jacob Thiem Variable Discharge Stallman Hantush Abu-Zeid & Scott Aron & Scott Lai *et al.* Moench Constant Drawdown Jacob & Lohman Hantush Rushton & Rathod Slug Test Hvorslev Cooper *et al.*
Yes		
Storage in Confining Bed	= No >	Without Storage Hantush & Jacob
Yes — >	——— >	With Storage Hantush Neuman & Witherspoon

Table SOP033-1. Decision tree for selection of aquifer test method (after ASTM D-4043-91).